Environmental Protection Series

Proposed Evaluation Protocol for Cement-based Solidified Wastes

Report EPS 3/HA/9
December 1991

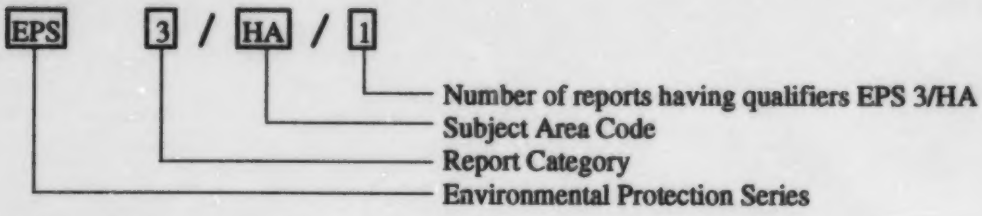
Canada

Environment Canada

Environnement Canada

ENVIRONMENTAL PROTECTION SERIES

Sample Number:



Categories

1 Regulations/Guidelines/Codes of Practice
2 Problem Assessments and Control Options
3 Research and Technology Development
4 Literature Reviews
5 Surveys
6 Social, Economic and Environmental Impact Assessments
7 Surveillance
8 Policy Proposals and Statements
9 Manuals

Subject Areas

AG Agriculture
AN Anaerobic Technology
AP Airborne Pollutants
AT Aquatic Toxicity
CC Commercial Chemicals
CE Consumers and the Environment
CI Chemical Industries
FA Federal Activities
FP Food Processing
HA Hazardous Wastes
IC Inorganic Chemicals
MA Marine Pollutants
MM Mining and Ore Processing
NR Northern and Rural Regions
PF Paper and Fibres
PG Power Generation
PN Petroleum and Natural Gas
RA Refrigeration and Air Conditioning
RM Reference Methods
SF Surface Finishing
SP Oil and Chemical Spills
SRM Standard Reference Methods
TS Transportation Systems
TX Textiles
UP Urban Pollution
WP Wood Protection/Preservation

New subject areas and codes are introduced as they become necessary. A list of EPS reports may be obtained from Environmental Protection, Conservation and Protection, Environment Canada, Ottawa, Ontario, Canada, K1A 0H3.

Think Recycling!

Please do regular!

This publication is printed on paper containing recovered waste.

Proposed Evaluation Protocol for Cement-based Solidified Wastes

Wastewater Technology Centre
Environment Canada

with the support of

U.S. Environmental Protection Agency
Office of Research and Development

and

Ontario Ministry of the Environment
Waste Management Branch

Report EPS 3/HA/9
December 1991

92-02362/

CANADIAN CATALOGUING IN PUBLICATION DATA

Main entry under title:

Proposed evaluation protocol for cement-based solidified wastes

(Report ; EPS 3/HA/9)
Issued also in French under title: Protocole d'évaluation proposé pour les déchets solidifiés à la base de ciment.
Includes an abstract in French.
Includes bibliographical references.
ISBN 0-662-19303-2
DSS cat. no. En49-4/3-9E

1. Factory and trade waste -- Leaching. 2. Hazardous wastes. 3. Refuse and refuse disposal -- Standards. I. Wastewater Technology Centre (Canada). II. Canada. Environment Canada. III. Ontario. Waste Management Branch. IV. United States. Environmental Protection Agency. Office of Research and Development. V. Series: Report (Canada. Environment Canada) ; EPS 3/HA/9.

TD897.5P76 1991 363.72'8 C92-099526-8

©Minister of Supply and Services Canada 1991
Cat. No. En 49-4/3-9E
ISBN 0-662-19303-2

Readers' Comments

Comments regarding the content of this report should be addressed to:

Julia Stegemann
Wastewater Technology Centre
867 Lakeshore Road
P.O. Box 5068
Burlington, Ontario
L7R 4L7

Cette publication est aussi disponible en français. Pour l'obtenir, s'adresser à :

Publications de la Protection de l'environnement
Conservation et Proection
Environnement Canada
Ottawa (Ontario)
K1A 0H3

Abstract

Many processes have been developed to chemically stabilize and solidify industrial wastes. These stabilization/solidification processes have the potential of greatly reducing or eliminating the leaching of contaminants, thereby offering long-term protection of the environment.

This evaluation protocol is a decision-making tool for managing stabilized/solidified (S/S) wastes. It could be used in a regulatory framework. For that purpose, the protocol is based on the measurement of several physical, engineering and chemical properties of S/S wastes in order to evaluate different utilization and disposal scenarios. Several of the testing methods in the protocol were evaluated in a cooperative project with the industry initiated by Environment Canada. Others are methods recommended by standards organizations in the fields of hazardous and radioactive wastes. Finally, some properties of S/S wastes are measured using methods that are still in their developmental stage.

The performance of a stabilization/solidification process is normally waste-specific, contaminant-specific and, to a certain extent, dependent on a utilization or disposal environment. The laboratory testing protocol proposed to estimate the long-term stability of S/S wastes takes into account both the waste properties and the utilization or disposal conditions. The protocol evaluates two levels of containment: Level 1, based on contaminant partitioning, and Level 2, based on physical entrapment.

A Level 1 evaluation involves measuring the amount of contaminants available for leaching from the S/S matrix and the chemical resistance to leaching. This approach evaluates a maximum potential risk. The amount of contaminant available for leaching is estimated using a finely ground sample, in a batch extraction test at a high liquid-to-solid ratio. Performance criteria are set for each contaminant in terms of amount available for leaching expressed as mass of contaminant leached per mass of S/S waste.

A Level 2 evaluation is limited to monolithic S/S wastes, recognizing the ability of a waste form to offer mass transfer resistance to the leaching of contaminants. This approach involves measuring the potential for slow release of contaminants

from S/S waste monoliths and matrix durability (i.e., its ability to maintain its integrity for a long period of time). A Level 2 evaluation is conducted only if the waste form does not meet the Level 1 criteria.

This protocol represents a first attempt at developing a management tool for solidified wastes that accounts for their physical, engineering and leaching properties as well as different disposal conditions. While a series of tests and performance criteria are proposed based on an existing body of knowledge, it is hoped that the protocol will evolve as the data base of measured properties is developed and as our understanding of the fundamental processes controlling long-term leaching improves with more characterization and modelling work.

Résumé

Il existe de nombreux procédés de stabilisation et de solidification chimiques des déchets industriels. Ces procédés permettent de réduire grandement ou d'éliminer la lixiviation de contaminants et d'assurer ainsi la protection à long terme de l'environnement.

Le présent protocole d'évaluation se veut un outil de prise de décision en vue de la gestion des déchets stabilisés/solidifiés (S/S). Il pourrait éventuellement être utilisé dans un cadre réglementaire. À cette fin, le protocole se fonde sur la mesure de plusieurs propriétés physiques, chimiques et mécaniques des déchets S/S dans le but d'évaluer différents scénarios d'utilisation et d'élimination. Un certain nombre de méthodes d'essai contenues dans ce protocole ont été analysées dans le cadre d'un projet mené par Environnement Canada en collaboration avec l'industrie. D'autres méthodes sont recommandées par des organismes de normalisation oeuvrant dans le domaine des déchets dangereux et radioactifs. Enfin, on utilise des procédés en cours d'élaboration pour mesurer quelques-unes des propriétés des déchets S/S.

L'efficacité d'un procédé de stabilisation/solidification varie normalement en fonction du type de déchet et de contaminant et, dans une certaine mesure, du milieu d'utilisation et d'élimination. Le protocole d'essai en laboratoire proposé pour mesurer la stabilité à long terme des déchets S/S tient compte à la fois des propriétés des déchets et des conditions d'utilisation ou d'élimination. Il évalue deux niveaux de confinement : le niveau 1, selon la division des contaminants et le niveau 2, selon l'emprisonnement physique.

Dans une évaluation de niveau 1, on mesure la quantité de contaminants susceptibles d'être lixiviés de la matrice S/S ainsi que la résistance chimique à la lixiviation. Cette méthode permet d'estimer un risque potentiel maximum. La quantité de contaminants susceptibles d'être extraits par lixiviation est mesurée à partir d'un échantillon finement broyé, soumis à un essai d'extraction discontinu, avec un rapport élevé liquide-solide. Les critères de rendement pour chaque contaminant sont établis sous forme de quantité susceptible d'être extraite, dont la valeur est exprimée en masse de contaminants lixiviés par masse de déchets S/S.

Une évaluation de niveau 2 est limitée aux déchets S/S monolithiques et tient compte de la capacité d'un bloc de déchets à offrir une résistance de transfert massique à la lixiviation des contaminants. Cette méthode comporte la mesure du potentiel de libération lente de contaminants à partir de monolithes de déchets S/S ainsi que l'estimation de la durabilité de la matrice (c.-à-d., sa capacité à maintenir son intégrité pendant une période prolongée). On n'effectue cette évaluation que si le bloc de déchets ne satisfait pas aux critères de niveau 1.

Ce protocole constitue la première tentative d'élaboration d'un guide de gestion des déchets solidifiés tenant compte des propriétés physiques, mécaniques et de lixiviation de ces derniers et des différentes conditions d'élimination. Alors qu'une série d'essais et de critères de rendement sont proposés à partir des connaissances actuelles, on espère que le protocole évoluera à mesure que la base de données sur les propriétés mesurées s'élargira et que notre compréhension des processus fondamentaux régissant la lixiviation à long terme s'améliorera, grâce à une recherche accrue dans le domaine de la caractérisation et de la modélisation.

Foreword

This document presents a rational approach to determining whether cement-based solidified wastes should continue to be classified as hazardous, and what disposal/utilization scenarios would be appropriate for these wastes based on their measured characteristics. One of the major purposes of this document is to develop a framework under which field studies can be initiated to gather data on the impact and applicability of the proposed waste management approach. A data base could thus be developed to provide information on the long-term suitability of these waste management options. The document is also intended to generate discussion on the proposed approach or alternatives.

This document, in its present form, does not represent regulations or guidelines for the disposal or utilization of "hazardous" and "non-hazardous" materials. Furthermore, it does not constitute endorsement by any government agency. It does, however, represent the expertise of individuals within a variety of organizations concerned with waste management, including Environment Canada, the Ontario Ministry of the Environment, the United States Environmental Protection Agency, the Netherlands Energy Research Foundation, ASTM Committee D 34 on Waste Disposal, and a number of private consultants and commercial waste management organizations.

Table of Contents

Abstract v
Résumé vii
Foreword ix
List of Figures xiii
List of Tables xiv
Glossary xv

Section 1
Introduction 1

Section 2
Objectives 2

Section 3
Scope and Assumptions 3

Section 4
Conceptual Leaching Model 4
4.1 Generic Description of a Cement-based Stabilized/Solidified Waste 4
4.2 Mechanisms of Leaching 5

Section 5
Utilization and Disposal Scenarios 8
5.1 Unrestricted Utilization 8
5.2 Controlled Utilization 8
5.3 Segregated Landfill 8
5.4 Sanitary Landfill 8

Section 6
Evaluation 9
6.1 Approach 9
6.2 Level 0 Evaluation: Information on Process and Sample Matrix 12
6.2.1 Process Description 14
6.2.2 Mass/Volume Change 14
6.2.3 Porosity/Saturation 14
6.2.4 Organic Content 14
6.2.5 Contaminant Concentration 14
6.3 Level 1 Evaluation: Chemical Immobilization 15
6.3.1 Initial Leachate Concentrations 16
6.3.2 Amounts of Contaminants Available for Leaching 16

6.3.3 Acid Neutralization Capacity 18
6.4 Level 2 Evaluation: Physical Entrapment 18
6.4.1 Contaminant Mobility in the Matrix 19
6.4.2 Hydraulic Conductivity 21
6.4.3 Physical Strength 21
6.4.4 Weathering 22
6.4.5 Biodegradability 22

Section 7
Data Base of Stabilized/Solidified Waste Properties 23
7.1 Level 0 Evaluation 23
7.2 Level 1 Evaluation 39
7.3 Level 2 Evaluation 40

Section 8
Summary 42

References 43

Appendix
Sources for Test Methods 45

List of Figures

1 Conceptual Leaching Model 6

2 Decision Flow Chart for the Proposed Evaluation Protocol 10

3 Operationally Defined Partitioning of Contaminants . . . 15

4 Predicted Cumulative Fraction Leached 21

5 Distribution Plot of Total Porosity 25

6 Distribution Plot of Initial Leachate Concentration
- a) Arsenic 25
- b) Cadmium 26
- c) Chromium 26
- d) Copper 27
- e) Lead 27
- f) Mercury 28
- g) Nickel 28
- h) Zinc 29
- i) Total Cyanide 29
- j) Phenol 30
- k) Pentachlorophenol 30

7 Distribution Plot of the Amount Available for Leaching
- a) Arsenic 31
- b) Cadmium 31
- c) Chromium 32
- d) Lead 32
- e) Mercury 33

8 Distribution Plot of Acid Neutralization Capacity 33

9 Distribution Plot of Contaminant Mobility in the Matrix
- a) Arsenic 34
- b) Cadmium 34
- c) Chromium 35
- d) Lead 35
- e) Total Cyanide 36
- f) Phenol 36
- g) Pentachlorophenol 37

10 Distribution Plot of Hydraulic Conductivity 37

11 Distribution Plot of Unconfined Compressive Strength . . 38

12 Distribution Plot of the Weathering Results
a) Freeze/Thaw Weathering 38
b) Wet/Dry Weathering 39

List of Tables

1 Selected Performance Indicators 9

2 Testing Protocol 12

3 Performance Criteria for Utilization and Disposal Scenarios 13

4 Proposed Criteria for the Amount Available for Leaching for Some Metals 13

5 Contaminant Concentrations in the Raw Wastes of the Cooperative Project (Stegemann and Côté, 1991). . . 24

Glossary

Advection: The movement of water under the influence of a hydraulic gradient.

Amount available for leaching: Amount of contaminant extracted in a serial batch test (for anions and organics) or using the sequential chemical extraction (for metals), as defined in Section 6.3.

Carbonation: Attack of concrete and alkaline materials by natural carbonic acid. Carbonation is characterized by the conversion of calcium hydroxide into calcium carbonate which may decrease the pore pH and weaken the matrix.

Contaminant: Typically undesirable trace constituent that renders another substance impure.

Dimensional stability: Property of a waste that can be formed into a definite shape which is retained after proper curing.

Durability: The ability of solidified wastes to resist physical wear and chemical attack.

Hydraulic cement: A material that cures in the presence of water to develop structural properties.

Hydraulic conductivity: A proportionality constant with the dimensions length divided by time, which relates the water velocity or flux to the hydraulic gradient in a porous medium.

Hydraulic gradient: The difference in hydraulic potential between two points, divided by the separation distance.

Initial leachate concentration: Concentration of contaminant measured in a distilled water extraction test at a liquid-to-solid ratio of 4:1 (as defined in Section 6.3.1).

Key property: Intrinsic property of a stabilized/solidified waste, considered independently of the test method.

Leachant: The liquid which contacts the sample specimen during a leaching test or which contacts the solid waste form at a disposal site.

Leachate: Leachant after contact with the waste.

Leachability: The susceptibility of a solid material to lose its soluble or sorbed constituents by the dissolving action of water.

Leachability Index: A dimensionless index value related to the leaching characteristics of solidified waste materials as measured by the leach test defined in ANSI/ANS-16.1-1986 standard.

Leaching: Removal of soluble constituents from a solid waste by contact with a liquid.

Leaching rate: The amount of a constituent of a specimen or solid waste form which is leached during one time unit (i.e., g/d).

Molecular diffusion: The spreading of molecules under the influence of a difference in chemical potential.

Monolithic: Massively solid, single, uniform.

Monolithic specimen: A stabilized/solidified waste specimen which, after curing for 28 days, has an unconfined compressive strength of at least 350 kPa.

Performance criterion: A limit set on a performance indicator.

Performance indicator: The result of a test method selected to represent an important property of a solidified waste.

Porosity: The ratio of void volume to the total volume.

Soil-like specimen: A stabilized/solidified waste specimen which, after curing for 28 days, has an unconfined compressive strength of less than 350 kPa.

Solidified waste: A waste liquid, solution, slurry, sludge or powder which has been converted to a stable solid by a solidification process.

Stabilization/solidification: Operations performed to render a waste suitable for a given utilization or disposal scenario and resulting in chemical and physical transformation of the waste.

Waste form: A stable solid body meeting specifications for final disposal.

Section 1

Introduction

Stabilized/solidified (S/S) wastes may be characterized for several purposes which impose markedly different requirements on the selection of test methods. For research purposes, a wide variety of testing methods may be used to gain an understanding of morphological, chemical, and engineering properties. Standard test methods are often used in research, but nonstandard methods are also employed since more information can often be gained from looking at a problem from different angles. For management purposes, standard testing methods and performance criteria are required to determine in a consistent manner the suitability of technologies applied to various wastes in different disposal scenarios. For the purpose of conducting treatability studies, simple and rapid testing methods are needed to prescreen formulations and select those that subsequently would be subjected to the management tests. Finally, S/S wastes can also be tested for quality assurance/quality control purposes, to verify that the performance obtained in the laboratory is reproduced and maintained under large-scale or field conditions.

This evaluation protocol is intended for use as a decision-making tool for managing solidified wastes. It could be used in a regulatory framework. It measures several physical, engineering and chemical properties of S/S wastes in order to evaluate different utilization and disposal options.

Several of the testing methods in this protocol were evaluated in a cooperative project with representatives of the waste stabilization/solidification industry (Stegemann and Côté, 1991 and 1990) initiated by Environment Canada. Other testing methods evaluated were the ASTM (American Society for Testing and Materials) or ANS (American Nuclear Society) standards or those borrowed from the protocol recommended by the U.S. Nuclear Regulatory Commission for low-level radioactive waste forms (Jungling and Greeves, 1989). Available test methods for leaching were surveyed, classified, and reviewed in another document (WTC, 1990). The main purpose of this document is to propose an approach for managing S/S wastes. It is recognized that, as development work continues and the data base grows, improved testing methods could be substituted for those available when this document was prepared.

Words or expressions with a special meaning in the context of this document are defined in the preceding glossary.

Section 2

Objectives

The main objective of this document is to propose an approach for evaluating the long-term leachability of stabilized/solidified wastes. Secondary objectives include the following:

1) to identify key properties of solidified wastes and major mechanisms of physical degradation and leaching;

2) to select easily measurable performance indicators corresponding to key properties in a laboratory testing program;

3) to identify test methods for the performance indicators; and

4) to set performance criteria for each performance indicator for four typical utilization and disposal scenarios for solidified wastes.

Section 3

Scope and Assumptions

The proposed protocol is comprised of a battery of laboratory-scale tests which can be run in most environmental and geotechnical laboratories. It was specifically developed for evaluating cement-based waste forms. A cement-based waste form is obtained by adding a hydraulic cement (such as portland cement, power plant fly ash, cement kiln dust, and ground blast furnace slag) to a waste. The technology is most successfully applied to inorganic wastes and must be customized for a specific waste stream. Although the protocol is mainly applicable to inorganic wastes, organic contaminants present in a mostly inorganic matrix can be evaluated provided that they are not volatile. Application of the performance criteria to either untreated wastes (e.g., incinerator residues) or waste forms prepared with materials other than hydraulic cements (e.g., wastes encapsulated in bitumen or glass) is currently outside the scope of the protocol.

The main potential of S/S wastes for contaminating the environment is considered to be leaching (through contact with infiltrating rain water or groundwater). Other exposure routes, such as volatilization or particle mobilization, are not addressed in this protocol.

The potential for leaching is a function of both the waste properties and the site conditions, whether it be a disposal site or a utilization scenario. This protocol is limited to measuring key waste properties related to the main leaching mechanisms, to determine the suitability of a waste for different disposal and utilization scenarios and to measuring those properties relevant to protecting the environment. For example, the physical strength required for long-term durability is investigated, but the strength required for a particular utilization scenario is not. For economic reasons, it is always preferable to utilize a waste rather than dispose of it, provided that this can be done in a way that does not pose an unacceptable risk to the environment.

Section 4

Conceptual Leaching Model

This section presents generic models of a cement-based waste form and leaching mechanisms for selecting performance indicators. The models are derived from a comprehensive review of the literature (WTC, 1990), a data base of S/S waste properties (Stegemann and Côté, 1991 and 1990) and mathematical modelling of leaching phenomena (Côté, 1986).

4.1 Generic Description of a Cement-based Stablized/Solidified Waste

From a macroscopic point of view, a properly performed stabilization/solidification operation results in a homogeneous mixture of waste and additives. The degree of intimate, microscopic mixing depends on the nature of the waste and additives as well as the method and intensity of mixing. Typically, the waste will be finely dispersed in the matrix with some occurrence of clumps. The clumps could correspond, for example, to the flocculated grains of metal sludge obtained through physical/chemical treatment of wastewater or to agglomerates of soil particles in a contaminated soil. Dimensional stability of the matrix is insured by the linking of the additive particles (and sometimes particles present in the waste) with the cementitious products to form a matrix skeleton. In the process, the clumps of waste are physically entrapped.

All cement-based S/S wastes are porous materials. Stegemann and Côté (1991) found that the porosity of 69 solidified products ranged from 0.16 to 0.81, with a median of 0.57. Côté (1986) showed that porosity is typically distributed among three different pore sizes: larger than 100 μm, approximately 1 μm, and smaller than 0.1 μm. The pores larger than 100 μm are voids between clumps of waste and/or additive particles. The pores of approximately 1 μm are inter-particle spaces within the clumps. Finally, the pores smaller than 0.1 μm include the voids inside solid particles (hydrated cement, fly ash, clay, etc). Tracer studies showed that only a fraction of the pores are linked to each other and to the exterior of the waste form. This fraction constitutes the connected porosity of the S/S waste. The pores which are not linked to this network constitute the closed porosity.

Initially, the pores of cement-based waste forms may only be partially saturated with water. This results from the mixing of dry additives that both absorb the water in the waste and use it in hydration reactions. When immersed in water, however, the matrix tends to become saturated with water.

The micro-morphology of the matrix determines how easily water can permeate through a S/S waste. It has been shown that the hydraulic conductivity of S/S wastes may vary over several orders of magnitude, from low values typical of compacted clays to high values similar to silty soils.

The durability of a S/S waste refers to its ability to resist physical wear and chemical attack. Physical mechanisms of degradation include wind and water erosion, and matrix breakdown as a result of freeze/thaw or

wet/dry cycles. Little data are available on erosion but it has been shown that S/S wastes can be disintegrated by repeated cycles of freezing/thawing or wetting/drying. Most solidified wastes can be made stronger and therefore more resistant to physical degradation by adding more cement and special concrete additives, although this increases additive cost and volume of waste.

Chemical mechanisms of degradation refer to the leaching action of water or other solutions on the skeleton of the matrix. Stabilized/solidified wastes have properties which suggest they would be chemically resistant in the environment. This is based on observations of the durability of similar materials (i.e., Roman pozzolanic cement) and on experimental results (Stegemann and Côté, 1991). The skeleton of S/S wastes normally consists of chemical compounds, such as minerals, amorphous metal oxides, and products of cement hydration, that have limited solubility in natural water. Also, the addition of cement establishes a stable, high pH environment in which most heavy metals have a very low solubility. The pore pH typically ranges from 11 to 13 and the matrix has a high acid neutralization capacity.

Carbonation is a potential degradation mechanism which has been extensively studied for concrete (Calleja, 1980), but has received little attention for S/S wastes. The isolation of S/S wastes from atmospheric carbon dioxide by burial suggests that carbonation should not affect their durability.

Biological degradation of S/S wastes is another mechanism which has received little attention, since the technology has been mainly applied to inorganic wastes. It should be noted, however, that the high pH established with cement is not favourable to biological growth even if the matrix contains a large amount of organic matter.

The containment of contaminants in a solidified waste matrix is a function of both physical and chemical mechanisms. From a physical point of view, contaminants can be classified by the ease with which they can be transported out of the matrix. The total amount of a contaminant may be associated with one of two fractions: 1) the fraction present in or adjacent to the connected porosity; and 2) the fraction present in or adjacent to the closed porosity. Little information is available on the physical distribution of contaminants in S/S matrices because the required microchemical and micromorphological techniques are painstaking, difficult to quantify, and often destructive.

Contaminants can also be classified by their chemical partitioning in the matrix. The total amount of a contaminant can be associated with either the pore solution or a component of the solid phase. Leaching of the fraction dissolved in the pore solution is only restricted by physical constraints. Whenever possible, wastes are treated to partition contaminants within a solid phase. The reversibility of the treatment reactions (i.e., the potential for the contaminants to be re-solubilized by the leachant) will determine whether or not the contaminants eventually become available for leaching.

4.2 Mechanisms of Leaching

The hydraulic conductivity of a S/S waste determines whether leaching will take place primarily by advection or molecular diffusion. For a hydraulic gradient around unity, diffusion can be neglected if the hydraulic conductivity is higher than 10^{-9} m/s (Shackelford, 1988). On the other hand, diffusion limits the rate of transport when hydraulic conductivity is lower than 10^{-9} m/s. When two materials with different

hydraulic conductivities are involved (i.e., a S/S waste and a surrounding soil), an analysis by Atkinson (1985) reveals that infiltrating rain water or groundwater flows mainly around or through the waste and may thus control the contaminant transport mechanism. If the hydraulic conductivity of the S/S waste is much lower (e.g., two orders of magnitude) than that of the surrounding material, water follows the path of least resistance by flowing mainly around the waste. In this case, leaching is limited by molecular diffusion in the connected porosity of the S/S waste matrix (even if the hydraulic conductivity of the S/S waste is higher than 10^{-9} m/s). When contaminants reach the S/S waste/surrounding material interface, they are carried away by the groundwater. If, on the other hand, the hydraulic conductivity of the solidified waste is on the same order of magnitude or higher than that of the surrounding material, water flows through the waste. The pore water solution is thus displaced and leaching takes place largely by advection.

Several transport mechanisms and chemical reactions that would constitute a comprehensive mechanistic leaching model are shown in Figure 1. A contaminant is initially present in the waste matrix in an immobile form (C_{im}) and in a mobile form (C_{mo}). The former is immobilized through both physical and chemical mechanisms (i.e., chemically in the solid phase and/or physically removed from the connected porosity). The mobile form is in solution in the connected porosity. The immobile fraction is subject to mobilization if the local equilibrium is disrupted as a result of the mobile form being transported by diffusion or advection.

Mobilization can occur by dissolution of precipitates, by desorption from solid surfaces, by transport from the closed pores of the matrix skeleton to connected porosity, or most likely, by a complex combination of these processes.

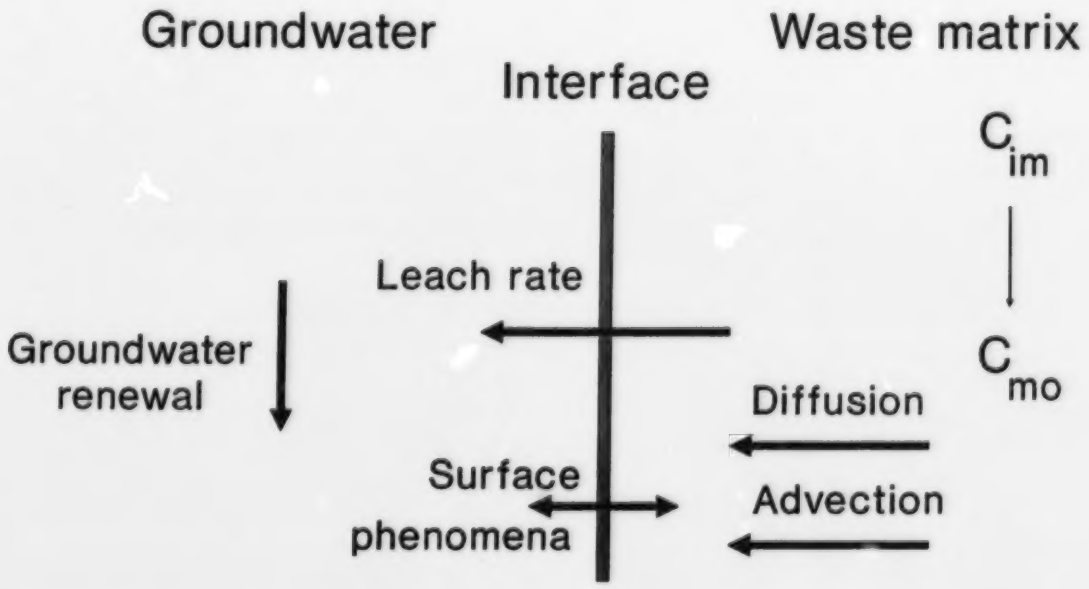


Figure 1 Conceptual Leaching Model

The surface phenomena shown in Figure 1 refer to chemical reactions between two normally quite different liquids, groundwater and leachate. Precipitation reactions may occur, changing the levels of soluble contaminants and modifying the morphology of the S/S waste and soil near the interface.

Simple mathematical models are available to estimate the relative importance of these various leaching mechanisms (Côté and Bridle, 1987). These models were used to identify the performance indicators presented in Figure 1.

Section 5

Utilization and Disposal Scenarios

The purpose of waste stabilization/ solidification is to maximize the containment of environmental contaminants. Whenever possible, utilization should be preferred over disposal in order to decrease the burden of land disposal. If a waste does require landfilling, however, the degree of environmental protection provided by stabilization/solidification should allow for disposal in less costly landfilling facilities, by reducing or eliminating the need for engineered barriers or liner systems.

For the purpose of this protocol, two utilization and two disposal scenarios have been selected that require different degrees of contaminant containment in a S/S waste. The scenarios are briefly described below, in order of decreasing performance requirements for a S/S waste.

Stabilized/solidified wastes that do not qualify for utilization or disposal according to one of these scenarios would need to be disposed in a secure landfill or subjected to a more effective treatment process. In a secure landfill, containment is more a function of engineered barriers and the host geological setting than of the waste properties. Space in a secure landfill is at a premium and waste treatment which increases volume is usually undesirable. The performance requirements for S/S wastes disposed in secure landfills are not addressed in this protocol.

5.1 Unrestricted Utilization

In an unrestricted utilization scenario, the S/S waste has a negligible leaching potential and may be used in any way that a natural material might be used, on land or in water (e.g., as a construction material). Once a given waste stream and stabilization/solidification process have been approved, the resulting product becomes exempt from waste management regulations.

5.2 Controlled Utilization

In this scenario, the leaching potential of the S/S waste is acceptable for a specific utilization (e.g., quarry rehabilitation, lagoon closure, road-base material). The environmental impact of S/S waste leachability measured with this protocol should be assessed and utilization approved on a site-specific basis.

5.3 Segregated Landfill

In this scenario, the S/S waste is not acceptable for utilization, or utilization is not possible or practical. The S/S waste is isolated from other wastes in a segregated landfill which does not necessarily have an engineered barrier or a leachate collection system.

5.4 Sanitary Landfill

In this scenerio, the S/S waste is not appropriate for utilization and is not acceptable for disposal in a segregated landfill without special engineered protection of the environment. Disposal with municipal garbage in a sanitary landfill is permitted.

Section 6

Evaluation

6.1 Approach

The leaching model described in Section 4 and illustrated in Figure 1 is a simplification of complex phenomena occurring under field conditions. The simplified model was used to identify key properties of S/S wastes related to their potential environmental impact in utilization and disposal scenarios. These key properties are listed in the second column of Table 1. One or several performance indicators are used to characterize each key property as listed in Column 3 of Table 1. A performance indicator is a direct experimental observation that is used as a measure of a key property.

The performance indicators were grouped into three categories, corresponding to basic information (Level 0), and two levels of containment (identified in Column 1 of Table 1):

Level 1 - containment by contaminant partitioning; and

Level 2 - containment by physical entrapment.

Figure 2 shows the hierarchy of levels and their relationship to the evaluation of the four utilization and disposal scenarios.

Table 1 Selected Performance Indicators

Level	Key Property	Performance Indicators	Expression
0	Sample preparation	Process description Mass/volume change	[w/ww] ratio
0	Matrix composition	Porosity/ Saturation Organic content Contaminant concentration	[w/v] [%] [%] [mg/wet kg], in waste
1	Contaminant partitioning	Initial leachate concentration Amount of contaminant available for leaching	[mg/L], of leachate [mg/wet kg], from waste
1	Chemical durability	Acid neutralization capacity	[equivalent/kg], in waste
2	Slow release (flow around)	Contaminant mobility in the matrix	Leachability index (diffusivity)
2	Slow release (flow through)	Hydraulic conductivity	[m/s]
2	Physical durability	Physical strength (before/after immersion) Weathering	[kPa] [% weight loss]
2	Biological durability	Biodegradability	[pass/fail]

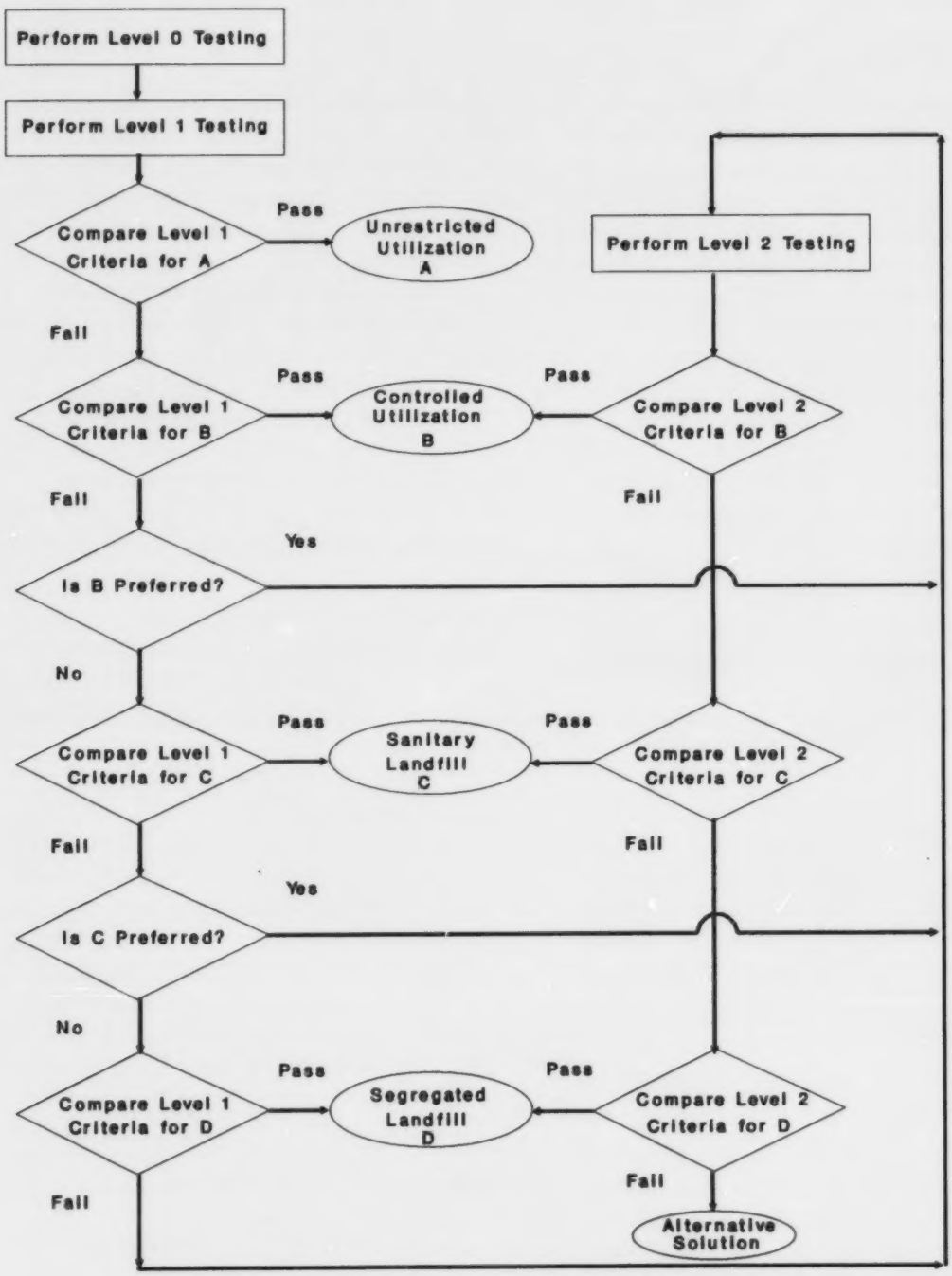


Figure 2 Decision Flow Chart for the Proposed Evaluation Protocol

A Level 0 evaluation involves obtaining basic information on the process and the S/S waste sample that is used to interpret the results of the Level 1 and 2 evaluations.

A Level 1 evaluation involves measuring the amount of leachable contaminants from the S/S matrix and the chemical resistance to leaching. No distinction is made between soil-like and monolithic materials. All samples are finely crushed before testing to ensure that particle size and physical integrity are not variables in the evaluation. This approach evaluates a potential risk based mainly on chemical mechanisms of containment. For a S/S waste that meets the performance criteria at Level 1, no special precautions are required to protect the waste from weathering during transport and placement operations, or after disposal.

A Level 2 evaluation is practically limited to monolithic S/S wastes since it evaluates the ability of a waste form to offer mass transfer resistance to the leaching of contaminants. This approach involves measuring the potential for slow release of contaminants from monolithic specimens. An important aspect of a Level 2 evaluation is the determination of the S/S waste durability. It is important that the integrity of S/S wastes approved at level 2 is protected by the operations of transport and placement of the waste as well as the long-term disposal conditions.

A flow chart of the procedure used to evaluate a S/S waste against this protocol is shown in Figure 2. First, the waste is subjected to Level 0 and 1 testing. The results are then compared against the Level 1 criteria for unrestricted utilization (denoted as "A" in Figure 2). If the waste passes the criteria, it is acceptable for unrestricted utilization. If it fails, the Level 1 results are compared with the Level 1 criteria for controlled utilization ("B"). If the waste passes these criteria, it is acceptable for controlled utilization. If it fails, either the Level 1 results are compared with the Level 1 criteria to determine if the waste is acceptable for disposal in a segregated landfill ("C"), or Level 2 testing is conducted to determine if the waste is acceptable for controlled utilization based on Level 2 criteria. This decision procedure can be repeated as indicated in Figure 2 to determine the suitability of the waste for the remaining disposal scenarios. If the waste fails both the Levels 1 and 2 criteria for disposal in a sanitary landfill ("D"), it must either be disposed in a secure landfill or, preferably, subjected to a new treatment technique and re-evaluated.

The rationale for selecting performance indicators and performance criteria is given in the following sections. Testing methods are recommended for each performance indicator in Table 2. For each testing method, the source is identified, the main features are described and potential problems are discussed. Methods requiring improvement or alternative methods are mentioned where appropriate. Performance criteria for each of the four utilization and disposal scenarios are proposed in Tables 3 and 4.

Whenever testing is conducted, variability is a critical issue in evaluating the validity of the measurements. Variability in results is usually a function of both the homogeneity of the waste, and the reproducibility of the test method. It is clearly essential to obtain measurements in the laboratory which are representative of the S/S waste form as a whole. A previous study of a number of the test methods recommended in this document (Stegemann and Côté, 1991 and 1990) has provided preliminary information concerning variability.

Table 2 Testing Protocol

Level	Performance Indicator	Testing Method	Recommended Method	Minimum Number of Replicates
0	Process description	No testing required	N/A	N/A
0	Mass/volume change	Bulk density	WTC Protocol, Method 2	3
0	Porosity/Saturation	Moisture content Bulk density Solids specific gravity	WTC Protocol, Method 4 WTC Protocol, Method 2 WTC Protocol, Method 3b	3 3 2
0	Organic content	Total organic content	(WTC, 1985)	3
0	Contaminant concentration	Digestion/extraction and analysis	(U.S. EPA, 1980)	3
1	Initial leachate concentration	Low liquid-to-solid ratio extraction	WTC Protocol, Method 9	4
1	Amount of contaminant available for leaching	Low pH extraction	Modified TCLP	4
1	Acid neutralization capacity	Titration with acid	WTC Protocol, Method 11	3
2	Contaminant mobility in the matrix	Dynamic leaching test	ANSI/ANS-16.1	1
2	Hydraulic conductivity	Falling head permeability	WTC Protocol, Method 5	4
2	Physical strength (before/after immersion)	Compressive strength	WTC Protocol, Method 6	4
2	Weathering	Freeze/thaw or Wet/dry cycles	ASTM D 4842-89 ASTM D 4843-89	4
2	Biodegradability	Biological growth	ASTM G 21-70 and G 22-76	3

Note: Sources for the test methods are given in the Appendix.

The data base generated by this previous work has been used as a basis for recommending a minimum number of replicates to be conducted for each of the test methods (Table 2). The results from these replicates can currently be used to quantify the variability of the performance indicators. In the future, it is anticipated that performance criteria will also be set for acceptable coefficients of variation for each of the properties being measured, although this is beyond the scope of the present document.

6.2 Level 0 Evaluation: Information on Process and Sample Matrix

The Level 0 evaluation provides basic information about the process and identifies contaminants to be monitored in the leaching tests. The organic content of the matrix is the only performance indicator for which a performance criterion must be set.

Stabilized/solidified waste samples prepared in the laboratory or obtained from a field operation are acceptable. Testing should be started after the samples have fully cured. The minimum proposed curing period is 28 days. Longer curing periods are acceptable but accelerated curing at high temperature is not as there are indications that this might induce phase changes in the matrix. General guidance on laboratory batch preparation, sample molding and curing is available in Stegemann and Côté (1991; Appendix B, Method 1).

Table 3 Performance Criteria for Utilization and Disposal Scenarios

Level	Performance Indicator	Expression	Utilization Scenarios		Disposal Scenarios	
			Unrestricted Utilization	Controlled Utilization	Segregated Landfill	Sanitary Landfill
0	Additive dosage	[w/ww]	N/A[1]	N/A	N/A	N/A
0	Mass/volume change	ratio	N/A	N/A	N/A	N/A
0	Porosity/ Saturation	[v/v] [%]	N/A N/A	N/A N/A	N/A N/A	N/A N/A
0	Organic content	[%], of waste	<1%[3]	<10%[3]	No limit[3]	No limit[3]
0	Contaminant concentration (Use this data to select target contaminants for monitoring in leachate.)	[mg/kg], in waste	No organics[3]	No organics[3]	No limit[3]	No limit[3]
1	Initial leachate concentration[2]	[mg/L], of leachate	Water quality limit (WQL)	5 x WQL	10 x WQL	100 x WQL
1	Amount of contaminant available for leaching[2]	[mg/wet kg], from waste	See Table 4	See Table 4	See Table 4	See Table 4
1	Acid neutralization capacity	[eq/kg], in waste	N/A	>1 (to pH=9)	>1 (to pH=9)	>3 (to pH=9)
2	Contaminant mobility in the matrix[2]	Leachability index (diffusivity)	N/A	>9	>8	>8
2	Hydraulic conductivity	[m/s]	N/A	$<10^{-9}$	$<10^{-8}$	$<10^{-9}$
2	Physical strength (after immersion)	[kPa]	N/A	350	350	3500
2	Weathering	[% weight loss]	N/A	Survive 12 cycles <10% weight loss	Survive 12 cycles <10% weight loss	Survive 12 cycles <10% weight loss
2	Biodegradability	[pass/fail]	N/A	N/A	Must pass if organic content >10%.	Must pass if organic content >10%.

[1] Not applicable.
[2] Criterion is applicable to every target contaminant.
[3] Local regulations may limit bulk concentrations of both organic content and organic and inorganic contaminants in wastes for utilization and land disposal.

Table 4 Proposed Criteria for the Amount Available for Leaching for Some Metals

Contaminant	Regulatory limit [1] expressed as		Criteria for Amount Available for Leaching [mg/wet kg waste]			
	Leachate Concentration [mg/L]	Amount Leached [mg/wet kg], of waste	Unrestricted Utilization	Controlled Utilization	Segregated Landfill	Sanitary Landfill
Arsenic	5.0	100	1	5	10	100
Barium	100.0	2000	20	100	200	2000
Cadmium	1.0	20	0.2	1	2	20
Chromium	5.0	100	1	5	10	100
Lead	5.0	100	1	5	10	100
Mercury	0.2	4	0.04	0.2	0.4	4

[1] Regulatory limits for the U.S. EPA TCLP (Federal Register, November 7, 1986). The factor of 20 between columns 2 and 3 corresponds to the liquid-to-solid ratio in the leachate test.

6.2.1 Process Description

A process description should include any pre-treatment of the waste, a list of additives and their dosages (some additives may be identified as proprietary), mixing equipment used, and the proposed field placement method (i.e., pouring, compacting). The additive dosages are used to calculate mass and volume changes resulting from stabilization/solidification. A chemical analysis of the additives for the contaminants of interest (Section 6.2.5) should be provided.

6.2.2 Mass/ Volume Change

The mass change from additives addition and the bulk densities of the raw and S/S waste are used to calculate the volume change (Stegemann and Côté, 1991). The recommended method for measuring bulk density is based on weighing a known volume of sample (Stegemann and Côté, 1991, Method 2).

6.2.3 Porosity/Saturation

Porosity and degree of saturation are useful to determine requirements for the testing program (i.e., the need for pre-saturation before testing for hydraulic conductivity) and to assist in interpreting several other tests. For example, in a S/S waste with a high porosity but a low degree of saturation, leaching may initially be low but could increase as the matrix becomes saturated.

Total matrix porosity and degree of saturation are calculated from measurements of moisture content, bulk density and solids specific gravity using soil moisture/density relationships (Stegemann and Côté, 1991). Moisture is determined by drying at 60°C to avoid driving off water of hydration (simplification of ASTM Standard D 2216-80 for the Laboratory Determination of Water Content of Soil, Rock, and Soil Aggregate Mixtures). The method for measuring solids specific gravity is based on the use of an inert gas because it has been found that S/S wastes are often partially soluble in water, which results in overestimation of the specific gravity if a method requiring water immersion is used.

6.2.4 Organic Content

Organic material (which is considered to be distinct from "organic contaminants", mentioned in Section 6.2.5) in a S/S waste can interfere with the cementing process (Cullinane *et al.*, 1987) and potentially lead to biodegradability of the matrix.

Particularly for the utilization scenarios, application of the technology should be restricted mainly to inorganic wastes for which it is most effective. A surrogate parameter, total organic carbon, is used as an indicator of the organic content. The organic content should be negligible (<1%) for the unrestricted utilization scenario, and limited to 10% for a controlled utilization scenario. Any level of organic content is acceptable for either of the disposal scenarios but if it exceeds 10% the effect of biological activity on potential degradation of the matrix or mobilization of contaminants should be demonstrated.

6.2.5 Contaminant Concentration

The raw waste should be fully characterized. Compounds that could interfere with the hydration of cement (Cullinane *et al.*, 1987) should be identified and quantified, as well as major inorganic and organic contaminants. While organic contaminants should be negligible for the utilization scenarios, the level acceptable for the two other scenarios is not limited *a priori*, although it might be controlled by other applicable regulations (e.g., wastes containing some organic contaminants may be excluded from land disposal). For

inorganic contaminants, a limit on the amount available for leaching is suggested in section 6.3.2 of this document, but limits may be imposed on bulk concentrations, subject to local jurisdiction.

A restricted number of contaminants should be selected as performance parameters in the leaching tests. The following guidance should be considered in selecting the contaminants to monitor in the leaching tests:

- select 4 to 6 contaminants with concentration in the raw waste of at least 100 times their detection limit in water;
- select typical cations (i.e., Cd, Pb), anions (i.e., As, Se) and organic compounds; and
- include a mobile tracer (i.e., Cl) to allow for distinction of physical and chemical containment (see Section 6.4.1).

Standard digestion and extraction methods should be used to identify and quantify contaminants in the S/S waste matrix (WTC, 1985; U.S. EPA, 1980). It is recommended that at least three aliquots be analyzed to characterize homogeneity of the contaminant in the waste. Since the purpose of stabilization/ solidification is to make the contaminants more difficult to extract, it is often more practical to measure contaminants in the raw waste and to calculate their concentration in the S/S waste by dividing by the mass change factor. In this case, it should be verified whether or not the stabilization/solidification additives contribute a significant amount of contaminants to the S/S matrix, and if so, their contribution should be accounted for.

6.3 Level 1 Evaluation: Chemical Immobilization

For Level 1 evaluation, the total amount of a contaminant present in a S/S waste matrix is partitioned into three fractions based on leaching potential. The three fractions are

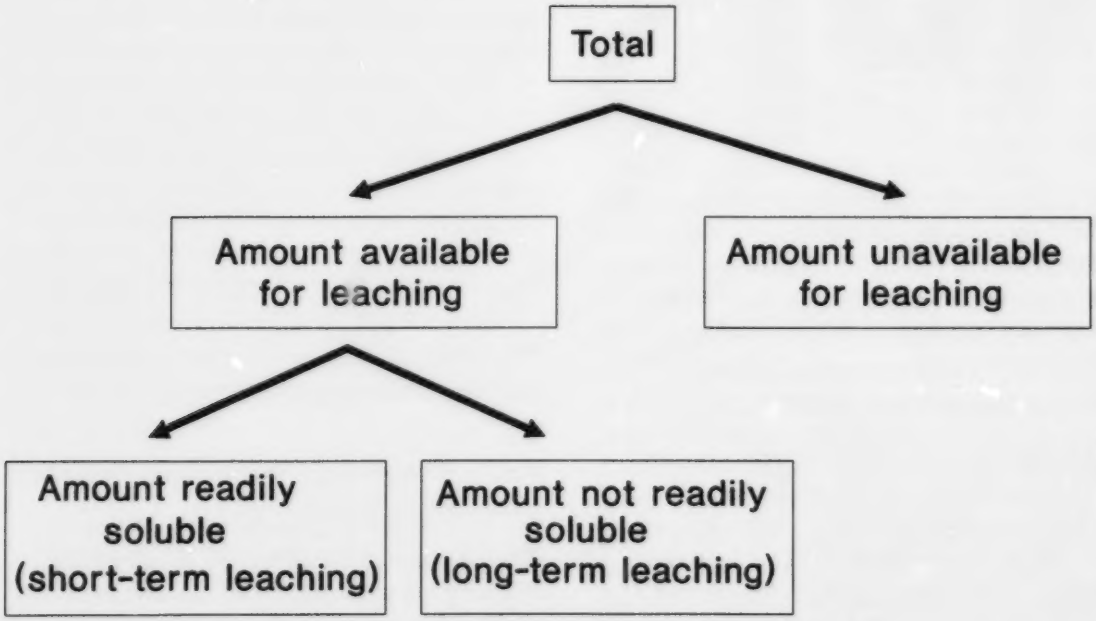

Total
Amount available for leaching
Amount unavailable for leaching
Amount readily soluble (short-term leaching)
Amount not readily soluble (long-term leaching)

Figure 3 Operationally Defined Partitioning of Contaminants

shown in Figure 3 and include: 1) the amount readily soluble, or, the initial leachate concentration; 2) the amount not readily soluble but available for leaching; and 3) the amount unavailable for leaching. Since the total amount is known from analysis of the waste (Level 0), two fractions must be determined experimentally to define the system completely. These two fractions, the amount readily soluble and the amount available for leaching, are estimated using extraction tests on crushed samples under different conditions. As the solubility of many heavy metals compounds is very dependent upon pH, the chemical resistance of the S/S waste to acid (e.g., lower pH site water) is also important.

Thus, in a Level 1 evaluation, three performance indicators of short- and long-term leachability must be compared with performance criteria for all selected contaminants. For water soluble compounds, such as anions and organic contaminants, the criterion based on the initial leachate concentration should cause an inferior S/S process to fail. For metals that are precipitated at high pH, the criterion based on the amount available for leaching should cause an inferior S/S process to fail.

The criterion for acid neutralization capacity ensures that the high pH of the S/S waste can be maintained over a very long period of time, ensuring long-term stability of metal compounds (particularly hydroxides).

6.3.1 Initial Leachate Concentrations

Initial leachate concentrations are measured with an extraction test using distilled water, at a liquid-to-solid ratio of 4:1 (Stegemann and Côté, 1991; Method 9). This ratio is a practical lower limit that provides enough leachate for analyses and good mixing, without too much dilution of the soluble species in the leachate, thus allowing the S/S waste to establish the chemical environment in the leachate. The waste is sufficiently crushed to pass through an ASTM #100 sieve (150 μm). This procedure yields steady-state concentrations in the leachate (Stegemann and Côté, 1991). Leachate pH should be measured and reported. At least four replicates of this test should be performed.

The concentrations measured in this extraction test are interpreted as concentrations in the pore water, or in an undiluted leachate. Performance criteria are set as multiples of applicable criteria for water quality (i.e., drinking water or reasonable-use guideline limits). For the unrestricted utilization scenario, no allowance is provided for dilution. For the controlled utilization scenario, the initial leachate concentrations are diluted by a factor of five. For the segregated landfill disposal scenario, a dilution factor of 10 is used in the criteria, while a dilution factor of 100 is used for the sanitary landfill disposal scenario. These dilution factors were set arbitrarily to account for attenuation, dilution, and degradation between the point of leachate generation and the point of water use. They are considered to be conservative when compared to the value of 100 used to set leachate limits in existing hazardous waste regulatory tests, i.e., the EPA Extraction Procedure Toxicity test (EPtox), Toxicity Characterization Leaching Procedure (TCLP), and similar procedures adapted by different Canadian provinces.

6.3.2 Amounts of Contaminants Available for Leaching

The amounts of contaminants available for leaching are measured in a way similar to that used in existing regulatory leaching tests, i.e., U.S. EPA EPtox and TCLP,

Ontario MOE Regulation 309 test. The amount available for leaching theoretically corresponds to that amount soluble in the leachant at infinite dilution and is thus measured in an extraction test at a high liquid-to-solid ratio. For metals, the highly buffered pH of a S/S matrix constitutes a masking effect. At infinite dilution, the acid neutralization capacity of the matrix would be depleted and a pH would be established that is representative of the field environment.

The amount of a metal available for leaching is thus measured by using an acidic leachant to accelerate natural neutralization phenomena. Existing extraction procedures, however, are not well suited for this protocol because the buffering capacity of the leachant is not high enough to maintain a constant pH in the leachate. The maximum amount of acid added in the EPtox or the TCLP is two equivalents of acid per kilogram of waste. This is normally not sufficient to consume the acid neutralization capacity of most S/S wastes (see Section 7, Figure 8). As a result, at the end of the test, the pH may vary considerably and the amount extracted does not reflect the amount available for leaching at low pH.

The recommended method is the U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP) test (Federal Register, 1990) with the following modifications:

1) the waste is crushed to pass through an ASTM #100 sieve (150 µm); and

2) the recommended extraction fluid is a 1 molar sodium acetate solution adjusted to pH=5 with acetic acid to create a buffer.

The first modification is necessary to obtain steady-state concentrations in the leachate. The second modification ensures that the pH will be buffered at a value of five with excess acidity. This extraction solution has been extensively used to leach metals from solidified wastes as Fraction B of the Sequential Chemical Extraction procedure (Stegemann and Côté, 1991; Method 12). An extraction period of 48 hours is required.

The results of the extraction test are expressed as amounts leachable (mg/kg of wet waste) rather than as concentrations. The concentrations measured in the leachate cannot be interpreted as representing concentrations in a field leachate and compared to standards for drinking water because the time distribution of leaching is not known.

At least four replicates of this test should be conducted to characterize variability.

Methods used to set performance criteria for the amount leachable should be based on direct comparisons with "accepted" materials (i.e., natural soils, concrete, bricks, asphalt, etc.) and/or considerations of soil and water protection through mathematical modelling (Côté, 1988). The use of existing regulatory criteria for classification of wastes is less rigorous but more practical. The leachate concentrations above which a waste is classified as hazardous according to the U.S. EPA EPtox and TCLP tests are given for several metals in column 2 of Table 4. The amount leached corresponding to that concentration was calculated and is presented in column 3 (the factor of 20 between columns 2 and 3 corresponds to the liquid-to-solid ratio). The recommended performance criteria for the four scenarios are also shown in the Table. The selected criteria represent fractions of the regulatory limits: 1/100 for the unrestricted utilization scenario; 1/20 for the controlled utilization

scenario; 1/10 for the segregated landfill; and 1/1 for the sanitary landfill scenarios.

The proposed criteria for the sanitary landfill are the same as those used to classify waste as hazardous or non-hazardous (using the regulatory extraction tests). Since the test method is more severe, however, the overall performance assessment is more stringent.

6.3.3 Acid Neutralization Capacity

The method recommended for measuring the acid neutralization capacity (ANC) of a S/S waste involves dividing a crushed sample into sub-samples, and mixing them with increasing amounts of a mineral acid for 48 hours before measuring the final pH (Stegemann and Côté, 1991; Method 11). This method ensures that a steady-state regime is reached. Alternatively, ANC could be measured using an automatic titrator. At least three replicates of this test should be done.

For the controlled utilization and segregated landfill scenarios, the ANC is 1 eq/kg of matrix to a final pH of 9. To appreciate the meaning of this value, it can be calculated that 1 kg of a S/S waste with an ANC of 1 eq can neutralize 10 000 L of a pH=4 mineral acid solution. The selected end point pH ensures that ANC is provided by the additive buffering system (i.e., products of cement hydration) rather than by precipitated metals. Even more acid would be required to attain a pH of 5, which would result in release of the entire amounts of contaminants that are "available for leaching" as described in Section 6.3.2.

For the sanitary landfill scenario, the required ANC is 3 eq/kg to a pH=9, to account for the fact that a S/S waste may be exposed to a higher amount of organic acid from the biodegradation of garbage.

Solidified wastes are very resistant to attack by an acidic leachant (such as acidic landfill leachate) provided that they remain monolithic and have a high acid neutralization capacity (Côté, 1986).

6.4 Level 2 Evaluation: Physical Entrapment

For a Level 2 evaluation, the potential for leaching is estimated from a monolithic specimen and the durability of that monolith is assessed.

In a field situation, the flow of leachant will be variable in space and time. The S/S waste may be continually immersed in leachant or subjected to wet and dry periods. Rather than trying to simulate any of these situations, which would require extensive site-specific information and comprehensive laboratory data, the approach used is to consider two extreme flow regimes: 1) water flowing completely around the waste; or 2) water flowing completely through the waste. Furthermore, actual leaching rates are replaced by performance indicators. These are based on worst case conditions, can be determined in a short period of time, and do not require extensive modelling.

The flow-around scenario is evaluated using an intermittent-flow dynamic leaching test. The flow is intermittent as opposed to continuous to simplify the procedure. The leachant renewal rate is high enough to maintain very small concentrations in the leachate, thus maximizing leaching rates. For cement-based waste forms, the rate of leaching is normally limited by the molecular diffusion of contaminants within the S/S waste matrix, a process which decreases with time. The leaching rates observed in a short-term test are therefore

the highest that could occur in such a leaching scenario.

A laboratory leaching test based on the flow-through scenario is impractical with S/S wastes. Their typically low hydraulic conductivity does not allow enough leachate samples to be collected over a short period of testing. As an alternative to a leaching test, hydraulic conductivity was selected as the performance indicator for the flow-through scenario.

Information on durability is required to extrapolate leaching results over time using mathematical models. It is assumed that durability is a direct function of the ability of the matrix to remain a monolith for a long period of time. While it can be argued that natural soils are not monolithic and still intrinsically durable, it is also true that soils have been completely leached of their soluble components. Therefore, the argument does not hold since the purpose of the testing program is to evaluate physical entrapment of potentially soluble contaminants.

Much is known about the durability of concrete made from portland or pozzolanic cement (Calleja, 1980), and the durability of cement-based waste forms can be inferred by drawing analogies. In this protocol, performance indicators of the S/S waste are measured to establish how closely the matrix resembles cured cement. A waste form that fails with respect to one of these performance indicators is not necessarily unacceptable, but it should be protected from degradation in the disposal environment. While it is recognized that durability is very much a function of the disposal conditions, this protocol evaluates basic properties related to physical, chemical, and biological mechanisms of degradation.

Selected performance indicators for physical durability include unconfined compressive strength (UCS) before and after water immersion, and resistance to freeze/thaw or wet/dry cycling. UCS is used as an indirect measure of the presence of cured cementing compounds. It is performed before and after immersion in water to ensure that the strength is due to cementing compounds, and not merely to drying. While a high UCS may not be required to provide dimensional stability in the landfill, it certainly indicates a more durable waste form.

The wet/dry and/or freeze/thaw cycling tests should be used to evaluate the resistance to weathering of a S/S waste matrix. This testing is intended to obtain an indication of short-term weathering resistance (i.e., during handling and landfilling) rather than to provide extensive data for a utilization scenario. More involved and appropriate testing methods could be borrowed from other fields (i.e., concrete) to obtain such data.

Since little is known about biological durability of S/S wastes, in this protocol the application of stabilization/solidification is limited mainly to inorganic residues. For S/S wastes containing a larger organic fraction than the specified limit, it must be demonstrated that the waste form would not support biological growth.

The performance criteria that must be met in a Level 2 evaluation are described in the following sections.

6.4.1 Contaminant Mobility in the Matrix

The mobility of contaminants in the matrix is estimated using the ANSI/ANS-16.1 protocol (American Nuclear Society, 1986). This method was selected because it represents an industry standard in the

radioactive waste field and is being used increasingly in the hazardous waste field. Although the method was originally developed for radioactive compounds, it has been shown that it can be applied to a wide range of contaminants, including organic compounds, provided that they are not volatile (Côté *et al.*, 1990). Only one replicate of this test is required, since each test consists of multiple leaching intervals.

The performance criteria for contaminant mobility in the matrix are Leachability Indices larger than nine for the controlled utilization scenario and larger than eight for the two disposal scenarios. The significance of these numbers can be evaluated by considering the results of a simple modelling exercise described in the following.

Under certain conditions outlined in the ANSI/ANS 16.1 protocol, the Leachability Index can be interpreted as the negative logarithm of an apparent diffusion coefficient in the S/S waste matrix. Modelling can be performed to estimate the efficiency of containment over time for a waste form leached in a flow-around mode. A simple diffusion model based on semi-infinite geometry provides a relationship to calculate the cumulative fraction leached as a function of time, based on the measured diffusion coefficient and the geometry of the waste form (Côté and Bridle, 1987; Côté *et al.*, 1987). The model assumes a zero surface concentration, which means that the flow of water around the waste form is sufficiently high to remove contaminants as they are leached. This model is applicable for cumulative fraction leached values smaller than 20%. For larger values, the assumption of semi-infinite geometry is violated and leaching is over-estimated.

Figure 4, constructed using the diffusion model, shows the cumulative fraction leached after 100 years as a function of the Leachability Index for three values of the surface-area-to-volume ratio: 0.6, 6.0 and 60 m^{-1} (these values correspond to cube shaped waste forms with a side dimension of 10 m, 1.0 m and 0.1 m, respectively). It can be seen that the formation of a large monolith decreases the surface-area-to-volume ratio and results in decreased leaching. The graph indicates that, for large monoliths (surface-area-to-volume ratio <6), the cumulative fraction leached after 100 years would not exceed 10% if the Leachability Index is larger than nine. Practically, because the flow of water around a waste form surrounded with soil is not sufficient to maintain a zero surface concentration, leached fractions would be smaller than the theoretical values.

Most stabilization/solidification technologies can meet these performance criteria for metals and for several organic compounds. For the more soluble inorganic salts (e.g., nitrates, chlorides) and organic compounds (e.g., phenolic compounds), a Leachability Index larger than eight is much harder to obtain. Exemption should be considered on a case-by-case basis by examining the total contaminant concentrations in the S/S matrix and Level 1 results.

A method was recently proposed to distinguish between physical and chemical mechanisms of containment (Côté *et al.*, 1990). This method, which involves measuring the Leachability Index of a soluble tracer (e.g., chloride) along with the contaminants of interest, provides additional information on the importance of durability on containment. However, no performance criteria have been developed for the method.

6.4.2 *Hydraulic Conductivity*

The hydraulic conductivity of a S/S waste is determined on a pre-saturated monolithic sample in a triaxial cell using a falling head method (Stegemann and Côté, 1991; Method 5). The method, however, has relatively poor reproducibility and alternate methods, such as the flow pump test, should be investigated (Znidarcic *et al.*, 1986). In any case, four replicates of hydraulic conductivity measurement should be performed.

The hydraulic conductivity criteria are $<10^{-9}$ m/s for the controlled utilization scenario and $<10^{-8}$ m/s for the disposal scenarios. These values were selected to prevent water from flowing through the S/S waste, thus forcing contaminants to be transported by slow molecular diffusion.

6.4.3 *Physical Strength*

Unconfined compressive strength (UCS) should be measured both before and after the S/S specimen has been immersed in distilled water for one week (Stegemann and Côté, 1991; Method 6). The recommended method was adapted from ASTM Standard C 109-80 for Compressive Strength of Hydraulic Cement Mortars. Other UCS methods, such as ASTM Standard D 1633, which allow for testing small cylinders, may also be used. Four replicates of this test should be performed.

The limit set for the controlled utilization and the segregated landfill scenarios is 350 kPa (50 psi), in accordance with a suggested EPA guideline (U.S. EPA, 1986). This physical strength is required to bear the weight of overburden and land-moving

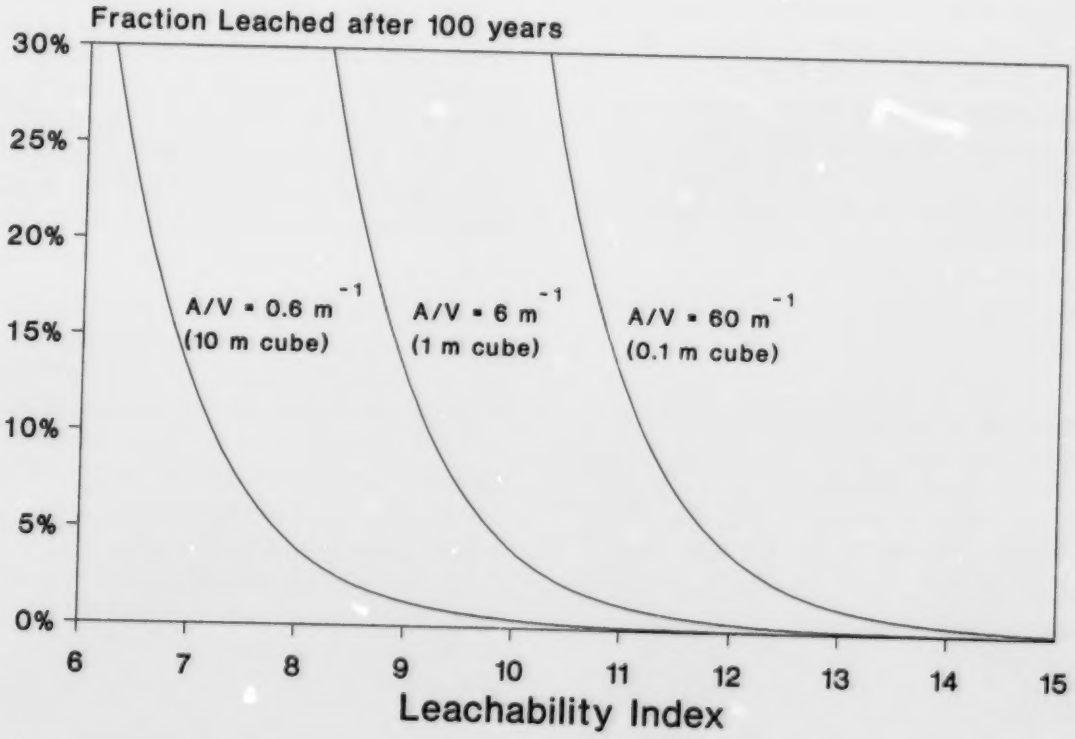


Figure 4 Predicted Cumulative Fraction Leached

equipment. For the sanitary landfill scenario, a higher strength (3500 kPa) is required for two reasons: 1) the compaction of municipal garbage might subject the dimensionally stable S/S wastes to higher stresses; and 2) the handling, placement and covering operations are not tailored to S/S wastes.

The UCS criteria listed in Table 3 are values after immersion. In addition to meeting these criteria, the UCS of the waste after immersion must not be less than 80% of the UCS before immersion.

6.4.4 Weathering

Results of both the wet/dry and freeze/thaw cycling tests are similar but the wet/dry procedure is easier and was found to be more reproducible (Stegemann and Côté, 1991). It is therefore the recommended method unless the freeze/thaw test is more relevant to the disposal environment. Both tests were developed in the cooperative project with industry (Stegemann and Côté, 1991; Methods 5 and 6) and have been adapted as standard methods by ASTM (Standard D 4842-89 for Freezing and Thawing of Solid Waste and Standard D 4843-89 for Wetting and Drying of Solid Waste). Four replicates of either test should be conducted.

The criterion established for either freeze/thaw or wet/dry weathering is survival of 12 cycles with a corrected weight loss of less than 10%. It is assumed that this is sufficient to ensure that the S/S waste will remain intact during placement operations in a landfill, until it is covered with soil and protected from exposure to the elements. The 10% limit for weight loss was selected because it represented a clear criterion for distinguishing between success and failure in an earlier study (Stegemann and Côté, 1991) summarized in Section 7.

6.4.5 Biodegradability

The potential for S/S waste biodegradation can be estimated from the total organic content (TOC) of a S/S waste. Biodegradation can be ruled out for S/S wastes with a TOC concentration lower than a set value. For S/S wastes with a concentration higher than that value, the potential for the matrix to support biological growth should be evaluated using the two following testing methods: ASTM Standard G 21-70, Standard Practice for Determining Resistance of Synthetic Polymeric Materials to Fungi, and ASTM Standard G 22-76, Standard Practice for Determining Resistance of Plastics to Bacteria. The application of these methods to cement-based waste forms is recommended by the U.S. Nuclear Regulatory Commission (Piciulo *et al.*, 1985). Although there is no experience base for the variability of this test at the Wastewater Technology Centre, at least three replicates should be conducted.

For both the segregated and sanitary landfill scenarios, the test to determine potential for biological growth needs to be run only if the total organic content of the matrix exceeds 10%. (For a controlled utilization scenario, the total organic content is limited to 10%.) The result is pass/fail and constitutes a screening test to verify if the S/S waste might support biological growth. If a failure result is obtained, further investigation should be done following the methods discussed in Piciulo *et al.* (1985).

Section 7

Data Base of Stabilized/Solidified Waste Properties

The performance criteria proposed in the previous section were chosen to ensure an adequate level of environmental protection. It is also necessary to compare the performance criteria to a data base of measured properties in order to determine whether the proposed level of performance for the four utilization and disposal scenarios is achievable with existing stabilization/solidification processes.

A large data base of S/S waste properties was developed in a cooperative project with 15 commercial participants organized by Environment Canada (Stegemann and Côté, 1991 and 1990). By distributing five raw wastes to the participants, 69 different S/S wastes were obtained and tested for their physical, engineering, leaching, and morphological properties. Although the testing program did not include all the testing methods included in this protocol, it represents the largest and most reliable data base of S/S waste properties.

In the cooperative project, all the performance indicators listed in Table 1 were measured, with the following exceptions.

1) The amount of contaminant available for leaching was estimated for metals only using the Sequential Chemical Extraction procedure, which is similar to the extraction method proposed in this protocol.

2) The contaminant mobility in the matrix was measured with a modified version of the ANSI/ANS-16.1 protocol which is believed to yield similar results.

3) Physical strength was measured after the samples were fully cured but not after they were immersed in water.

4) Biodegradability of the matrix was not measured.

The data from the original report of the cooperative project were reduced and expressed in the units used in this protocol. Distribution plots of the measured properties are presented in Figures 5 to 12 and are discussed in the following sections. The Y axis of every graph represents the percentage of data points with a lesser value than that read on the X axis. The legend for waste identification is given in Table 5.

A complete statistical analysis of the results is presented in the original report (Stegemann and Côté, 1991) and summarized in Stegemann and Côté (1990).

7.1 Level 0 Evaluation

The five raw wastes included in the cooperative study were scanned for inorganic and organic contaminants in order to determine a set of target contaminants to monitor in all the leaching tests. The selected target contaminants and their concentrations are presented in Table 5. The concentrations in the 69 solidified products were obtained by calculation, (i.e., by dividing the concentrations in the raw wastes by the mass change factors, assuming that

Table 5 **Contaminant Concentrations in the Raw Wastes of the Cooperative Project (Stegemann and Côté, 1991)**

Waste #	Waste Name	Contaminant	Average Concentration [mg/kg, w/ww]
1	WTC Synthetic Solution	Arsenic	2400
		Cadmium	4560
		Chromium	1570
		Lead	8050
		Phenol	3720
2	WES Synthetic Solution	Cadmium	3980
		Chromium	18400
		Nickel	19200
		Mercury	230
3	Aluminium Coil Plating Solution	Arsenic	11
		Chromium	1030
		Lead	43
		Thallium	17
		Total Cyanide	1790
4	Dredged Sediment	Chromium	220
		Copper	72
		Lead	150
		Mercury	0.7
		Zinc	940
		Polychlorinated Biphenyls	6.6
		Total Organic Carbon	90000
5	Wood Preservation Waste Soil	Arsenic	70
		Lead	70
		Mercury	0.02
		Pentachlorophenol	11200
		Polyaromatic hydrocarbons	310

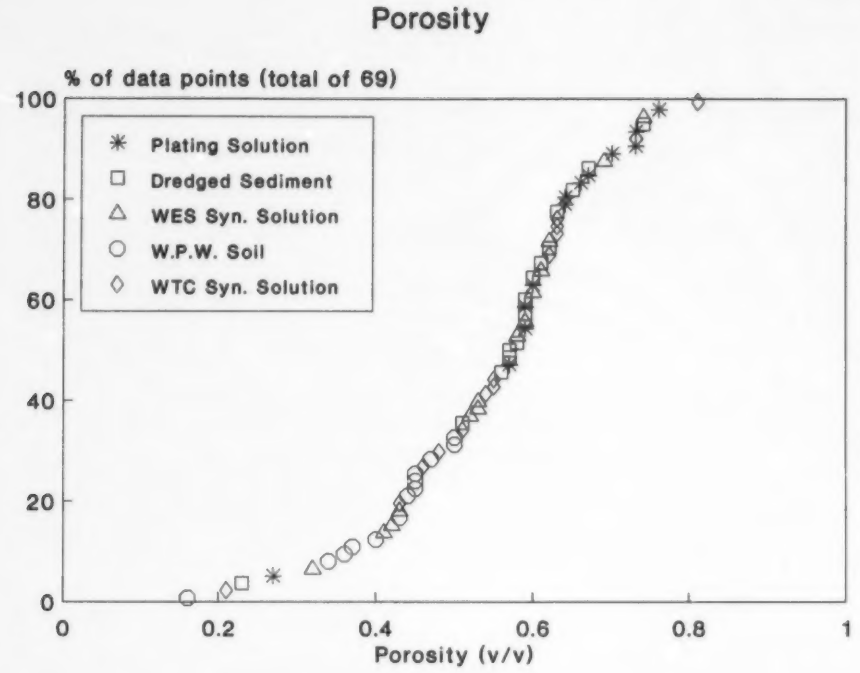


Figure 5 Distribution Plot of Total Porosity (Stegemann and Côté, 1989)

a) Arsenic

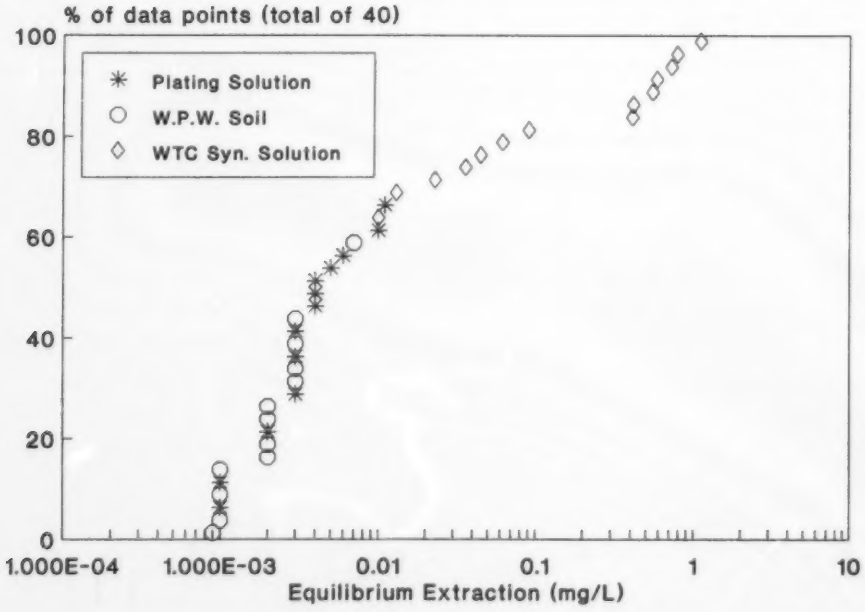
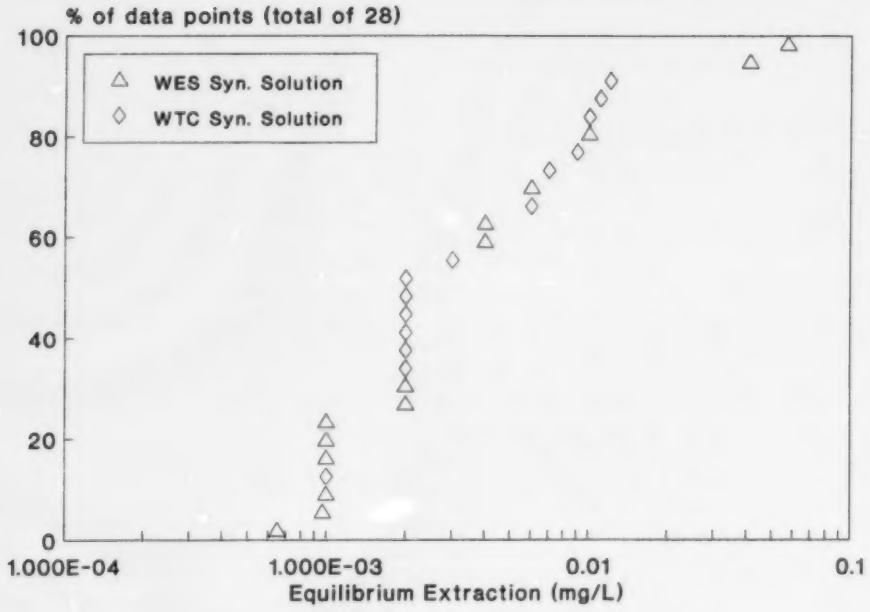


Figure 6 Distribution Plot of Initial Leachate Concentration (Stegemann and Côté, 1989)

b) Cadmium



c) Chromium

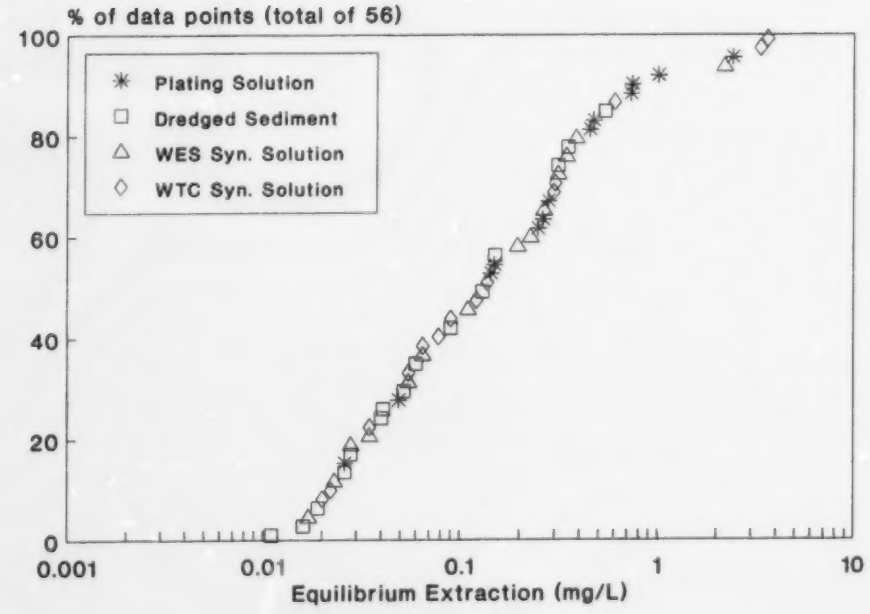
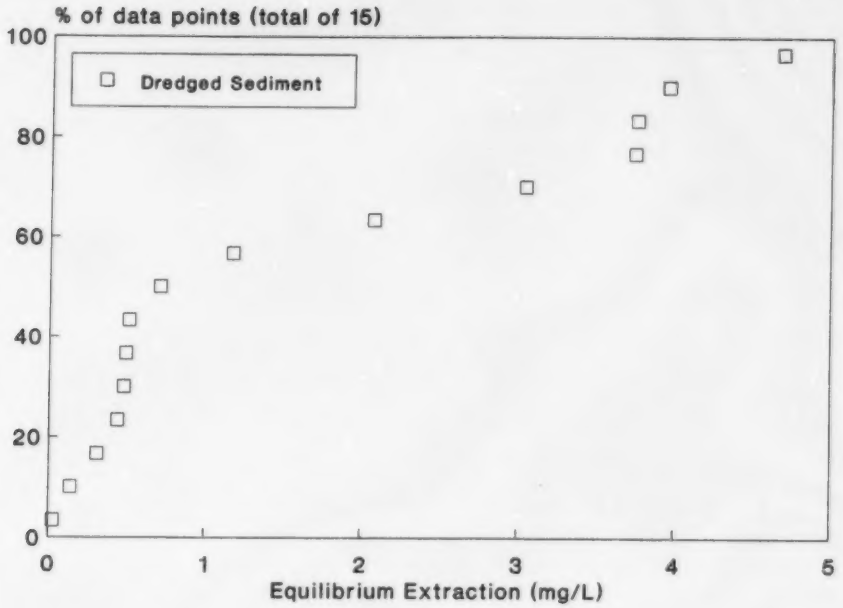


Figure 6 Distribution Plot of Initial Leachate Concentration (Stegemann and Côté, 1989) (Cont.)

d) Copper



e) Lead

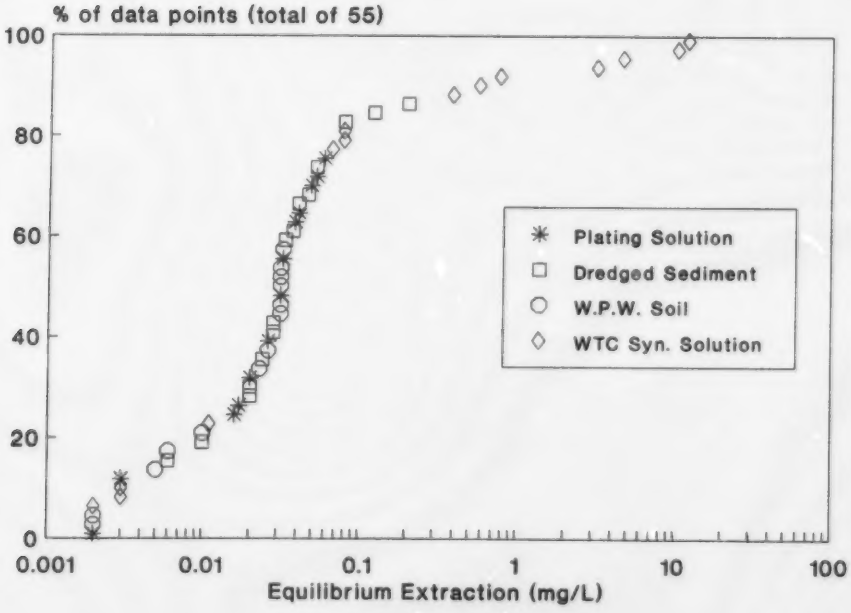
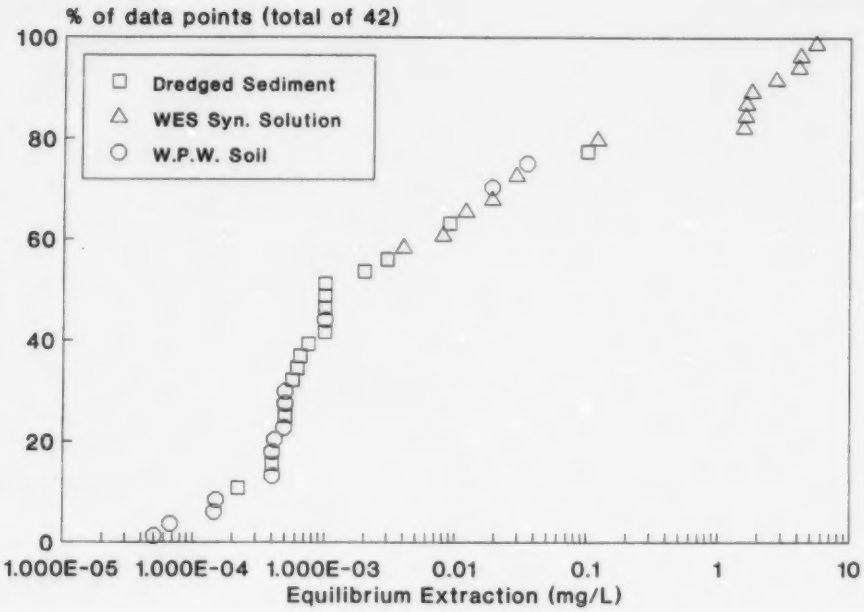


Figure 6 Distribution Plot of Initial Leachate Concentration (Stegemann and Côté, 1989) (Cont.)

f) Mercury



g) Nickel

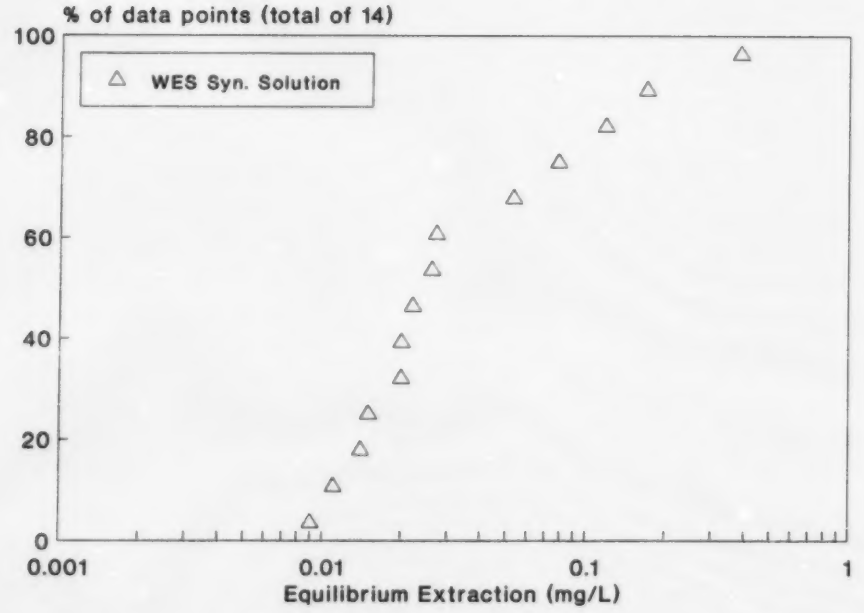
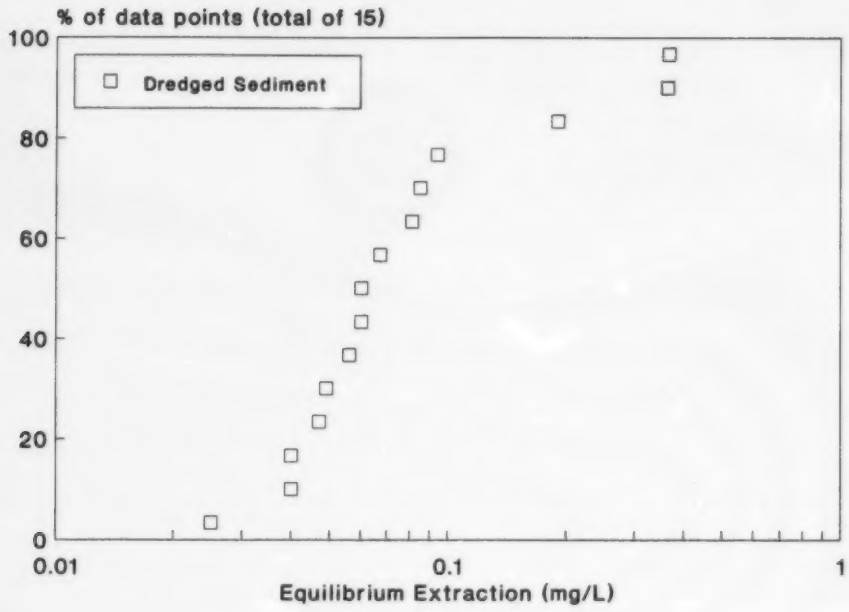


Figure 6 Distribution Plot of Initial Leachate Concentration (Stegemann and Côté, 1989) (Cont.)

h) Zinc



i) Total Cyanide

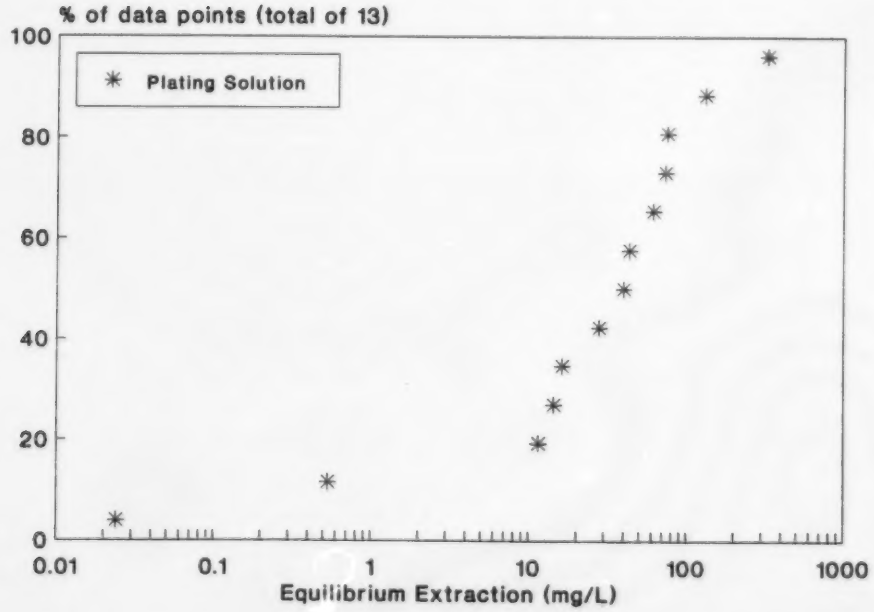
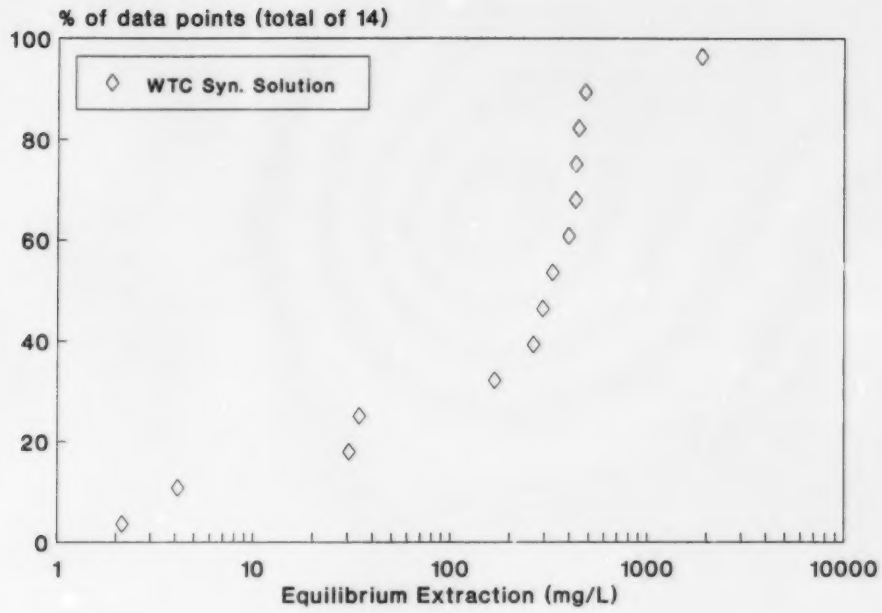


Figure 6 Distribution Plot of Initial Leachate Concentration (Stegemann and Côté, 1989) (Cont.)

j) **Phenol**



k) **Pentachlorophenol**

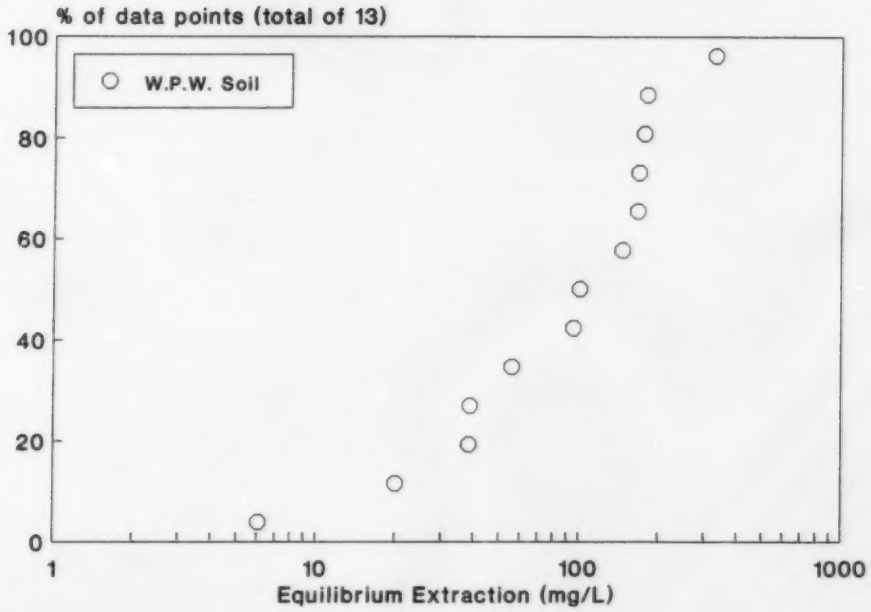
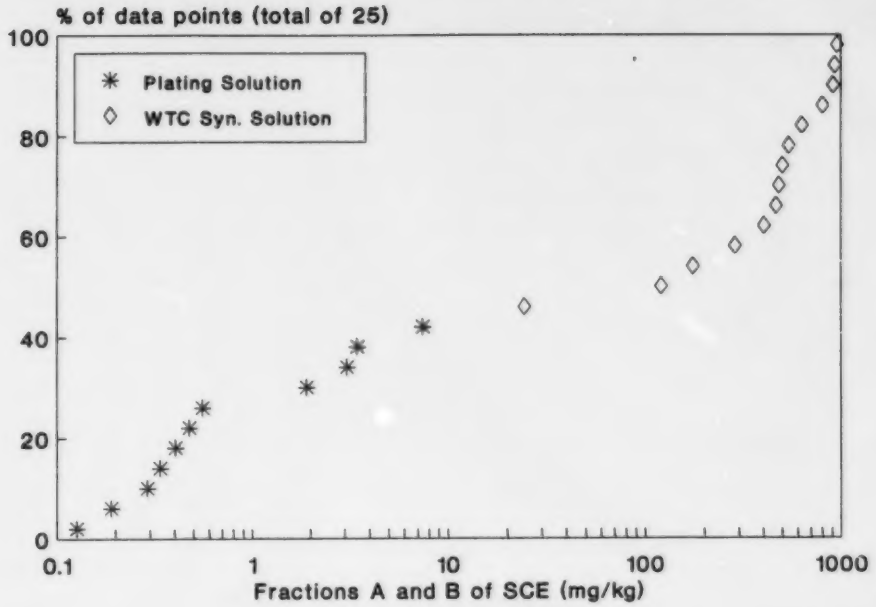


Figure 6 Distribution Plot of Initial Leachate Concentration (Stegemann and Côté, 1989) (Cont.)

a) Arsenic



b) Cadmium

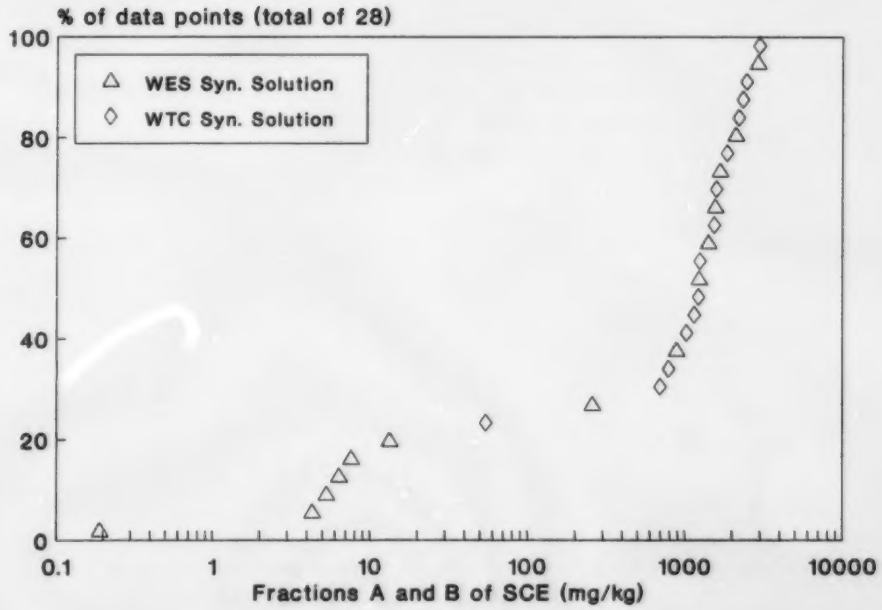
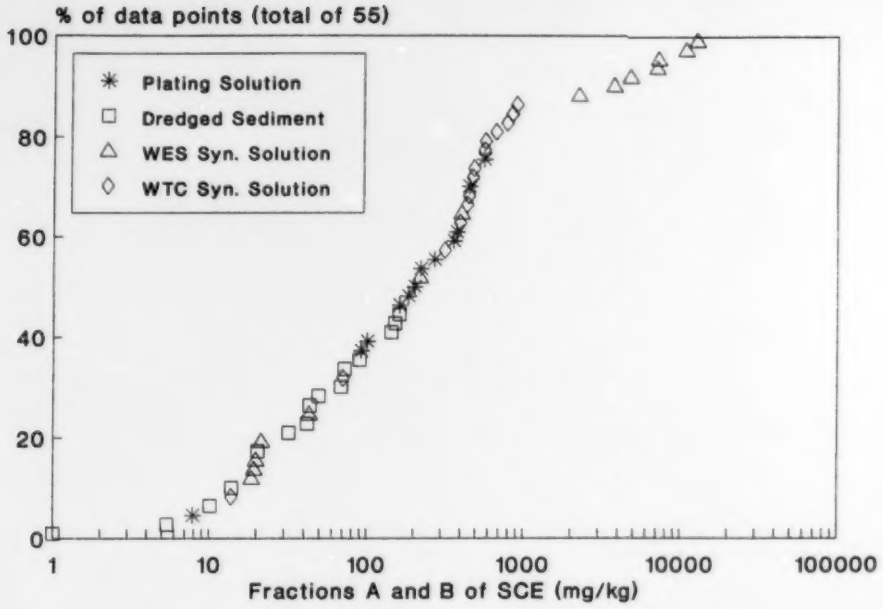


Figure 7 **Distribution Plot of the Amount Available for Leaching (Stegemann and Côté, 1989)**

c) Chromium



d) Lead

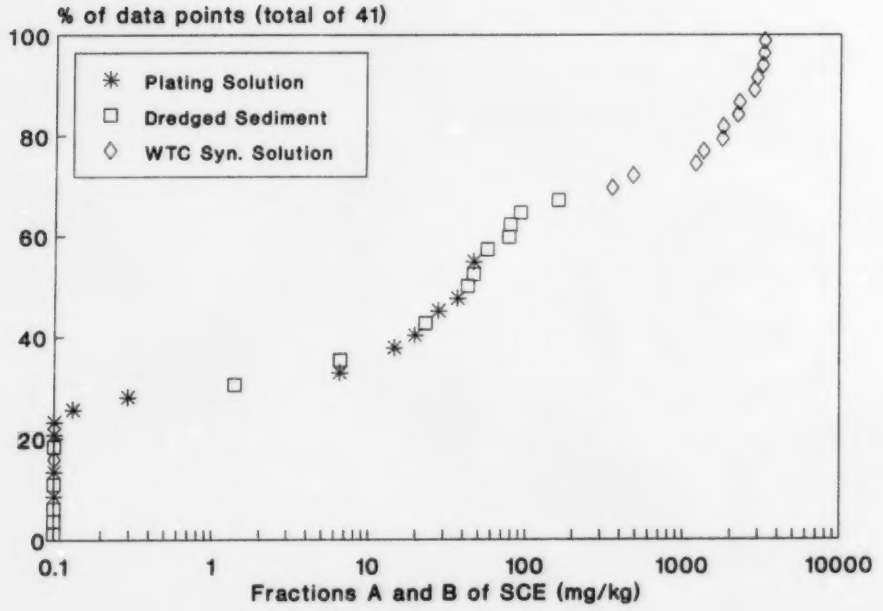


Figure 7 **Distribution Plot of the Amount Available for Leaching (Stegemann and Côté, 1989) (Cont.)**

e) Mercury

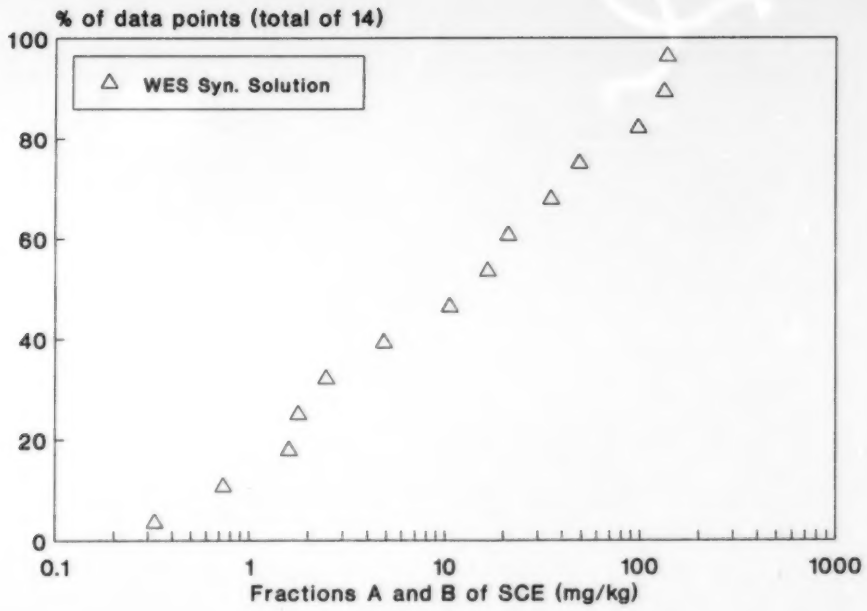


Figure 7 **Distribution Plot of the Amount Available for Leaching (Stegemann and Côté, 1989) (Cont.)**

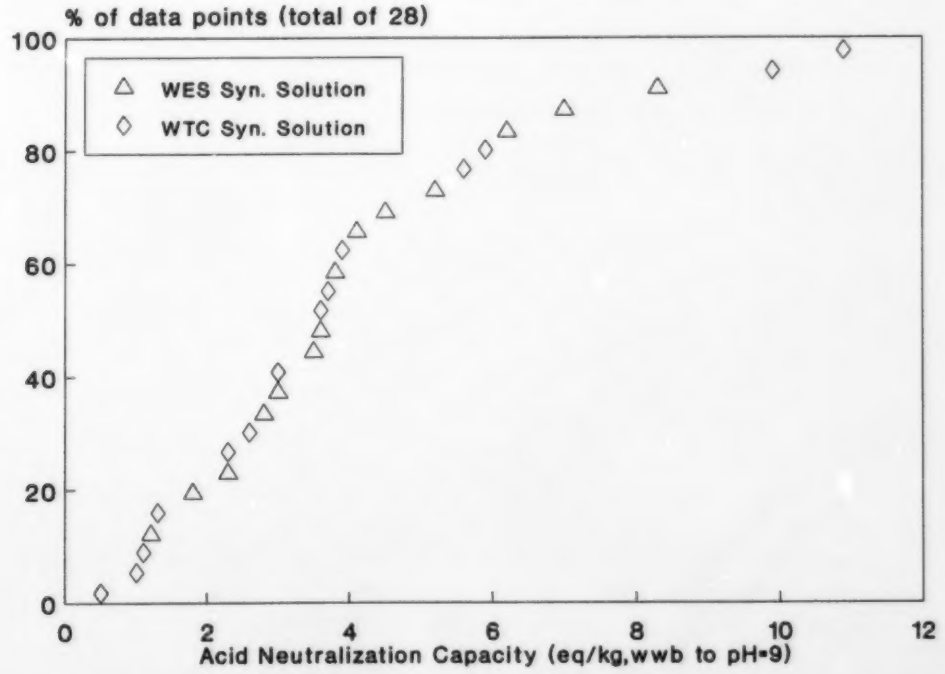
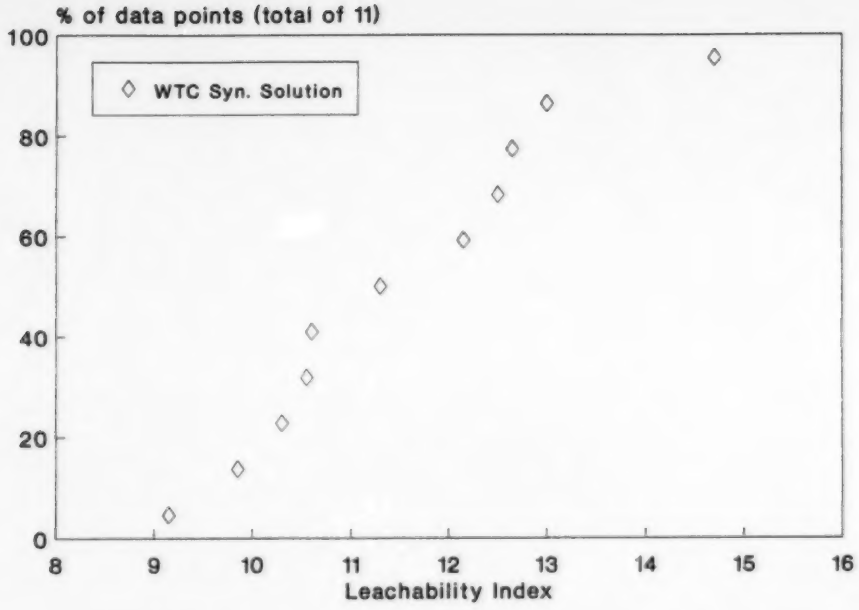


Figure 8 **Distribution Plot of Acid Neutralization Capacity (Stegemann and Côté, 1989)**

a) Arsenic



b) Cadmium

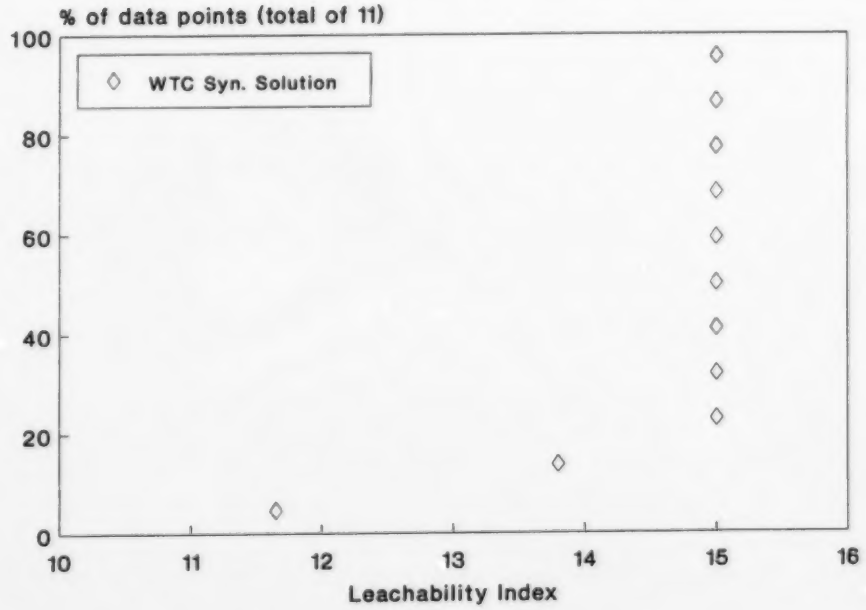
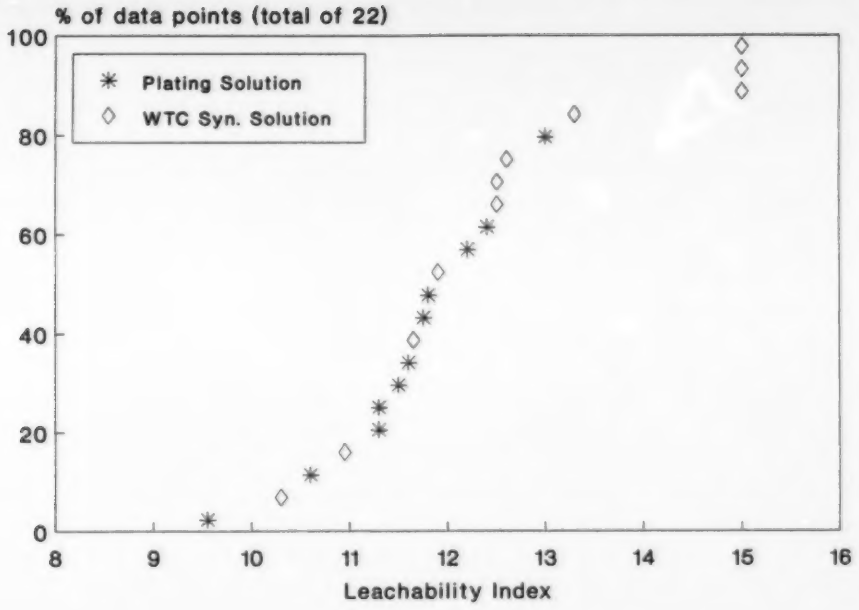


Figure 9 Distribution Plot of Contaminant Mobility in the Matrix (Stegemann and Côté, 1989)

c) **Chromium**



d) **Lead**

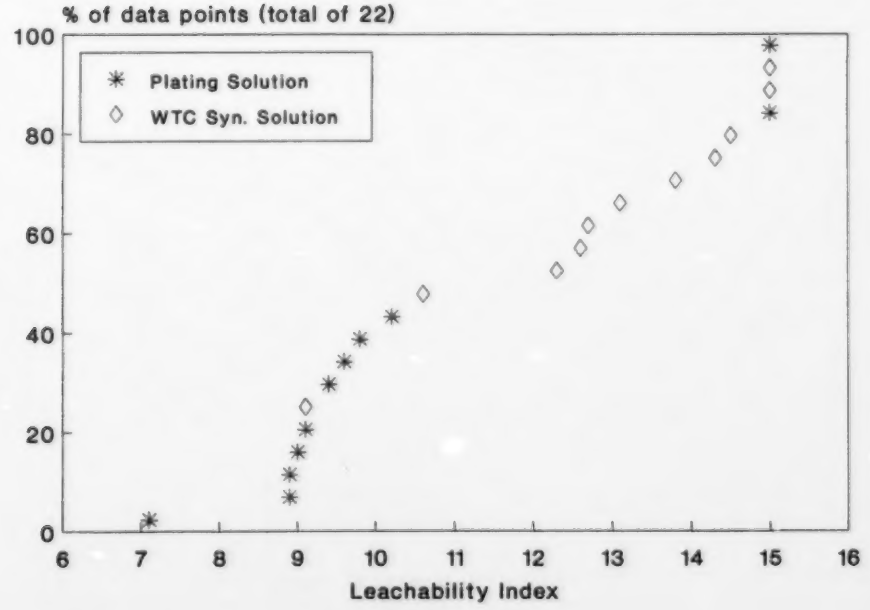
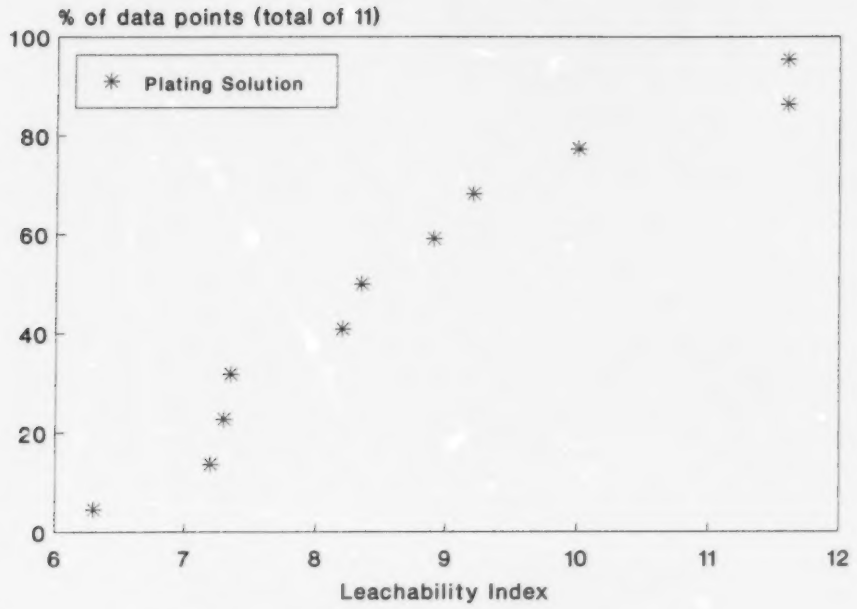


Figure 9 **Distribution Plot of Contaminant Mobility in the Matrix (Stegemann and Côté, 1989) (Cont.)**

e) Total Cyanide



f) Phenol

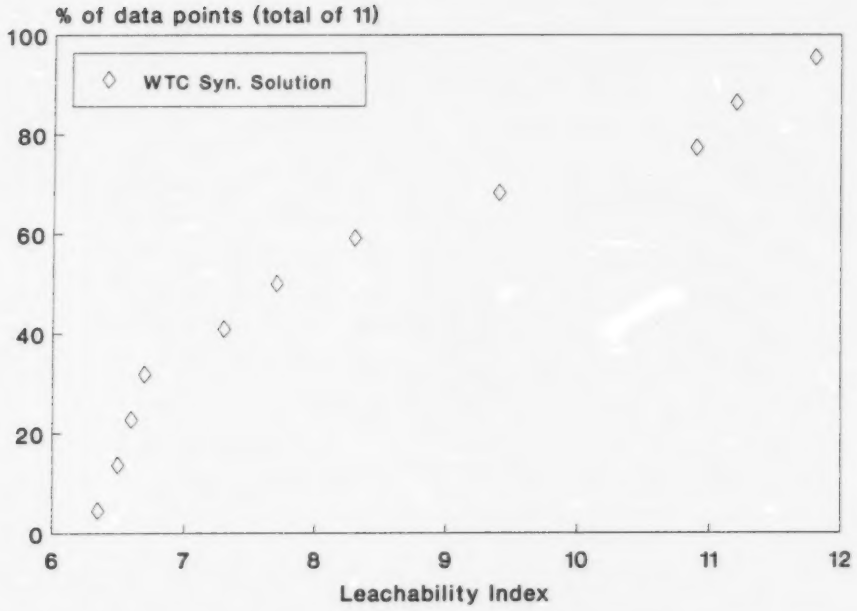


Figure 9 Distribution Plot of Contaminant Mobility in the Matrix (Stegemann and Côté, 1989) (Cont.)

g) Pentachlorophenol

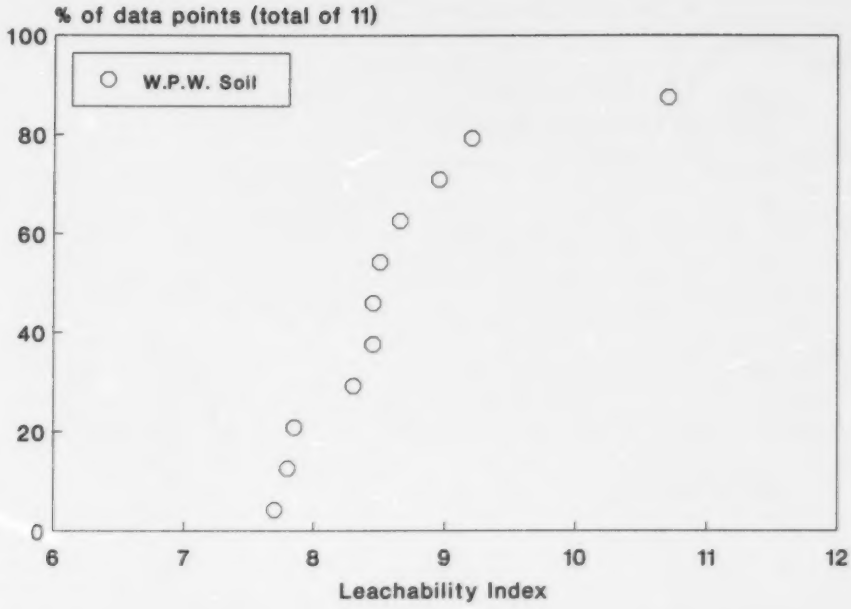


Figure 9 **Distribution Plot of Contaminant Mobility in the Matrix (Stegemann and Côté, 1989) (Cont.)**

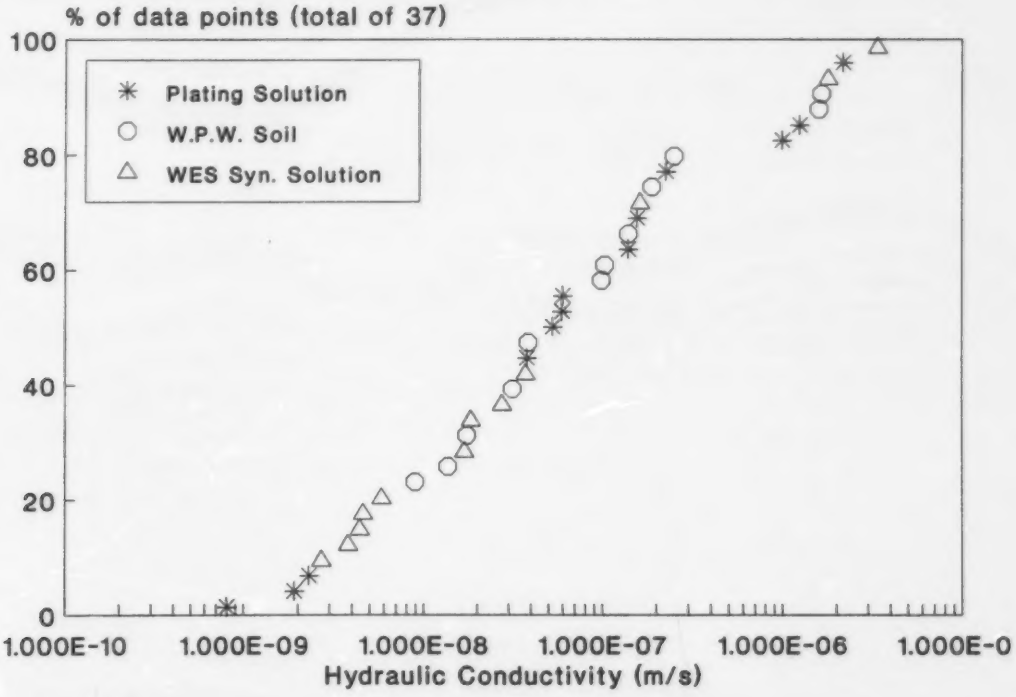


Figure 10 **Distribution Plot of Hydraulic Conductivity (Stegemann and Côté, 1989)**

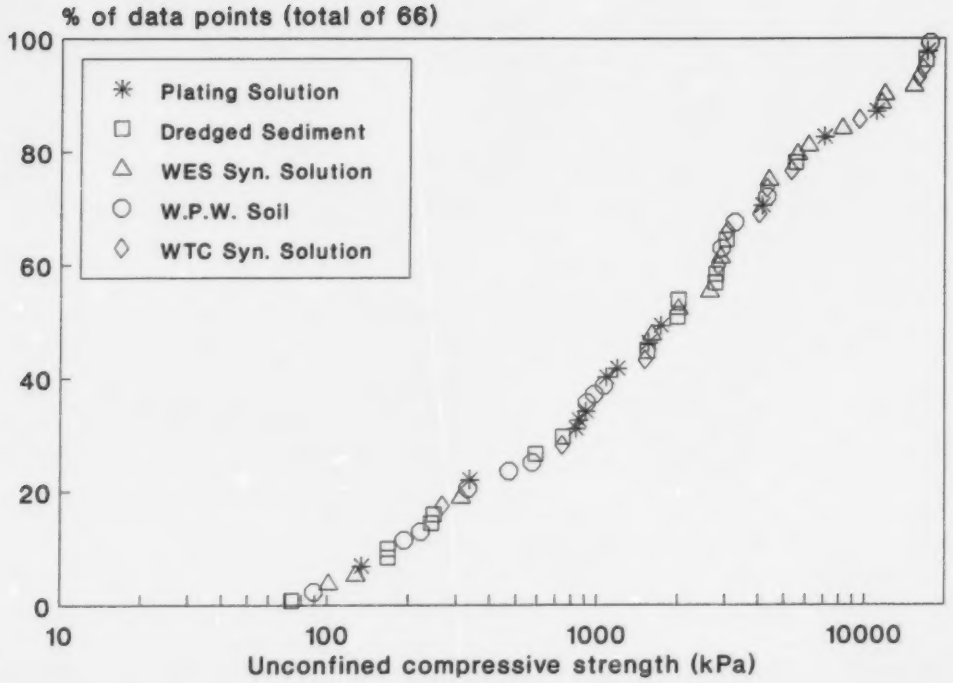


Figure 11 **Distribution Plot of Unconfined Compressive Strength (Stegemann and Côté, 1989)**

a) Freeze/Thaw Weathering

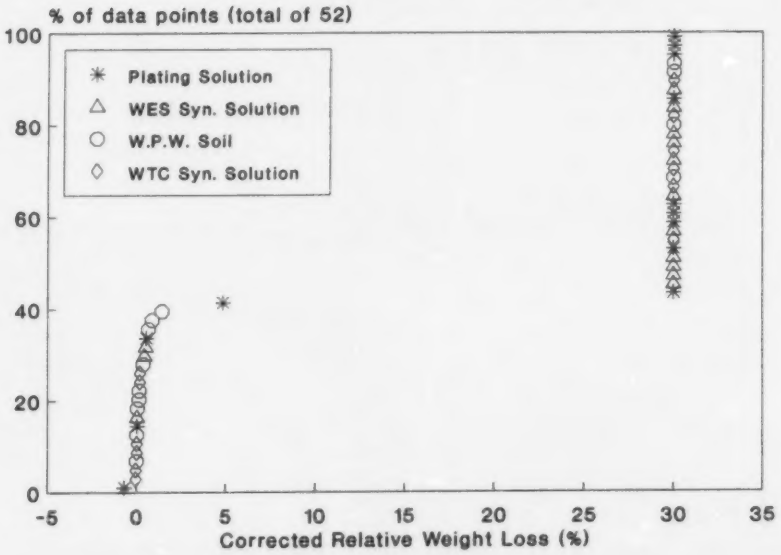


Figure 12 **Distribution Plot of the Weathering Results (Stegemann and Côté, 1989)**

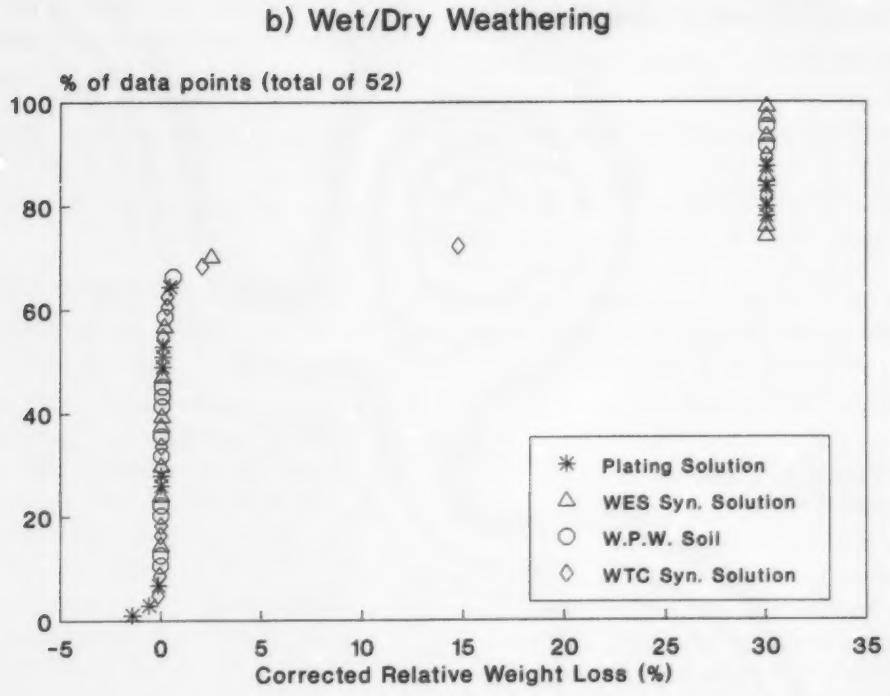


Figure 12 Distribution Plot of the Weathering Results (Stegemann and Côté, 1989) (Cont.)

there were negligible amounts of contaminants in the additives). The weight change factors for the solidified products ranged from 1.14 to 6.04, with a median of 1.79.

The measured porosities of the 69 products are presented in Figure 5, with values ranging from 0.16 to 0.81. Although no limit is imposed on porosity, this observation confirms that all cement-based solidified wastes are more or less porous. This is helpful for interpreting the results of the other tests.

7.2 Level 1 Evaluation

The initial leachate concentrations and the amounts of contaminant available for leaching are presented in Figures 6 and 7, respectively. Performance criteria for both properties must be met for a S/S waste to qualify for a certain scenario at Level 1.

The initial leachate concentrations of the contaminants shown in Figure 6 can be compared to drinking water guidelines (National Health and Welfare, 1987):

arsenic = 0.05 mg/L
cadmium = 0.005 mg/L
chromium = 0.05 mg/L
lead = 0.05 mg/L
copper = 1.0 mg/L
mercury = 0.001 mg/L
zinc = 5 mg/L

total cyanide = 0.2 mg/L
nickel, phenol and pentachlorophenol = not specified.

For arsenic, cadmium, lead, mercury, copper and zinc, most of the solidified waste initial leachate concentrations are lower than the drinking water guidelines. Few of the S/S leachates had chromium concentrations above the drinking water guideline whereas many of the leachates contained relatively large concentrations of total cyanide, phenol and pentachlorophenol.

The amounts available for leaching are presented in Figure 7 as the sum of Fractions A and B of the Sequential Chemical Extraction procedure (Stegemann and Côté, 1991; Method 12). The sum of these two fractions should give results similar to the modified TCLP method recommended in this protocol to measure the amounts available for leaching. Comparing these amounts to the criteria of Table 4, it can be seen that this test method is useful for differentiating among S/S processes.

The distribution plot of acid neutralization capacity (Figure 8) shows that essentially all solidified wastes meet the criterion for the controlled utilization and segregated landfill scenarios (1 eq/kg to pH=9). Most of the solidified wastes tested meet the criterion for sanitary landfill (3 eq/kg to pH=9).

In summary, a Level 1 evaluation appears very stringent. Only inorganic contaminants that are chemically bound in the matrix will be able to generate "initial leachate concentrations" that will conform to drinking water guidelines. The presence of organic contaminants or cyanide would probably cause a failure at Level 1. Very few S/S wastes would meet the "amount available for leaching" performance criteria for the utilization scenarios but several could meet the criteria for segregated or sanitary landfill. The severe testing methods and demanding performance criteria of Level 1 effectively force a Level 2 evaluation except for wastes with low concentrations of inorganic contaminants or S/S processes that show exceptional performance.

7.3 Level 2 Evaluation

The contaminant mobility in the matrix data, expressed as leachability indices, are presented in Figure 9. Solidified wastes for metals, such as arsenic, cadmium, chromium and lead, easily meet the performance criteria of 8 and 9 specified for the different scenarios. For cyanide, phenol and pentachlorophenol, however, only a fraction of the products can meet the performance criteria.

Figure 10 shows that a small fraction (20%) of the tested solidified wastes had a hydraulic conductivity smaller than the performance criteria proposed for segregated and sanitary landfill scenarios (10^{-8} m/s). Only one solidified waste could meet the criterion for controlled utilization scenario (10^{-9} m/s). These criteria, therefore, appear to be very severe. However, a low hydraulic conductivity is the single most important property to ensure durability by preventing contact with water and forcing diffusion-controlled leaching. The concrete technology has solutions for preparing low hydraulic conductivity matrices and it is felt that these solutions could easily be applied to solidified wastes.

The unconfined compressive strength data plotted in Figure 11 indicate that most solidified waste products can meet the specified criteria of 350 kPa and 3500 kPa . Physical strength can easily be increased by

adding more cement, at the expense, however, of a corresponding increase in volume.

Freeze/thaw and wet/dry weathering performances after 12 cycles are presented in Figure 12 as corrected cumulative weight losses. Specimens that did not survive 12 cycles were assigned a weight loss of 30% (weight losses greater than 30% were not measured). The data show a clear difference between durable and non-durable solidified wastes. Specimens that survived 12 cycles did so with little weight loss (<3%).

In summary, the recommended performance criteria for a Level 2 evaluation fall within the ranges of measured properties for the solidified wastes tested. The testing methods are therefore useful in determining acceptable and unacceptable performance. The data indicate that improvement is needed in the following two areas: 1) the containment of organic contaminants; and 2) the reduction of hydraulic conductivity.

Section 8

Summary

This protocol represents a first attempt at developing a management tool for solidified wastes. Stabilized/solidified wastes are characterized in three levels of testing, to determine the relative importance and efficacy of chemical and physical mechanisms of containment. Results from testing are used to determine the suitability of the waste form for utilization or disposal in one of four different scenarios (as shown in Figure 2). Whereas the series of tests (Table 2) and performance criteria (Tables 3 and 4) are proposed based on an existing body of knowledge, it is hoped that the protocol will evolve as the data base of measured properties is developed and as our understanding of the fundamental processes controlling long-term leaching improves with more characterization and modelling work.

In particular, a field study should be conducted to evaluate the protocol's ability to characterize the properties of a S/S waste. Such an undertaking would assist in setting realistic performance criteria and improve understanding of the variability of the performance indicators. Since the full protocol, as described here, is designed for thorough initial evaluation of a solidification process, as applied to a specific waste, it is also desirable that screening tests be developed for more efficient quality control.

References

AIChE, "Dry Solids, Paste and Dough Mixing Equipment", American Institute of Chemical Engineers, New York (1979).

American Nuclear Society, "Measurement of the Leachability of Solidified Low-level Radioactive Wastes by a Short-term Test Procedure", Method ANSI/ANS-16.1 (1986).

Atkinson, A., "The Influence of Wasteform Permeability on the Release of Radionuclides from a Repository", *Nuclear and Chemical Waste Management, 5*:203-214 (1985).

Calleja, J., "Durability", *Proceedings of the 7th International Congress on the Chemistry of Cement*, Editions Septima, Paris (1980).

Côté, P.L., "Contaminant Leaching from Cement-based Waste Forms under Acidic Conditions", Ph.D. Thesis, McMaster University (1986).

Côté, P.L., "Leaching Criteria for the Utilization and Disposal of Ashes", *Proceedings of a Municipal Solid Waste Ash Utilization Conference*, Philadelphia. (October 13-14, 1988).

Côté, P.L. and T.R., Bridle, "Long-term Leaching Scenarios for Cement-based Waste Forms", *Waste Management & Research, 5*:55-66 (1987).

Côté, P.L., R. Caldwell, and C.C. Chao, "Physical and Chemical Containment of Organic Contaminants in Solidified Wastes", *Waste Management, 10*:95-102 (1990).

Côté, P.L., T.W. Constable, and A. Moreira, "An Evaluation of Cement-based Waste Forms Using the Results of Approximately Two Years of Dynamic Leaching", *Nuclear and Chemical Waste Management, 7*:129-139 (1987).

Cullinane, J., M. Bricka, and N. Francingues, "An Assessment of Materials that Interfere with Stabilization/ Solidification Processes", *Proceedings of the 13th Annual Research Symposium*, Hazardous Waste Engineering Research Laboratory, United States Environmental Protection Agency, Cincinnati, Ohio (May 2-8, 1987).

Federal Register, Part II, Environmental Protection Agency, 40 CFR Part 261 *et al.*, "The Hazardous Waste Management System: Identification and Listing of Hazardous Waste: Toxicity Characteristics Revision: Final Rule", Vol. 55, No. 61, (March 29, 1990).

Government of Ontario, "Regulation 309. Revised Regulations of Ontario, 1980, as Amended to Reg. 138/90 under *Environmental Protection Act*", Environment Ontario (January, 1990).

Jungling, T. and J. Greeves, "NRC Regulations and Experience with Solidification/Stabilization Technology", in: *Environmental Aspects of Stabilization and Solidification of Hazardous and Radioactive Wastes*, Côté, P. and Gilliam, M. (eds.), ASTM STP 1033, American Society for Testing and Materials, Philadelphia (1989).

National Health and Welfare Federal-Provincial Subcommittee on Drinking Water, "Guidelines for Canadian Drinking Water Quality" (1987).

Piciulo, P.L., C.E. Shea, and R.E. Bartella, "Biodegradation Testing of Solidified Low-level Waste Streams", Report NUREG/VCR-4200, BNL-NUREG-51868, Prepared by Brookhaven National Laboratory for U.S. Nuclear Regulatory Commission (1985).

Shackelford, C.D., "Diffusion as a Transport Process in Fine-grained Barrier Material", *Geotechnical News, 6*(2):24-27 (1988).

Stegemann, J. and P.L. Côté, "Investigation of Test Methods for Solidified Waste Evaluation - A Cooperative Program", Report EPS 3/HA/8, Environment Canada (1991).

Stegemann, J. and P.L. Côté, "Summary of an Investigation of Test Methods for Solidified Waste Evaluation", *Waste Management, 10*:41-52 (1990).

U.S. EPA (The United States Environmental Protection Agency), "Test Methods for the Evaluation of Solid Wastes, Physical/Chemical Methods", SW-846, Office of Water and Waste Management, Washington, DC (1980).

U.S. EPA (The United States Environmental Protection Agency), "EPA Statutory Interpretive Guidance Document #530-SW-86-016" (June, 1986).

WTC (Wastewater Technology Centre), "Analytical Methods for the Investigation of Test Methods for Solidified Waste Characterization", Internal Document (1985).

WTC (Wastewater Technology Centre), "Compendium of Waste Leaching Tests", Report EPS 3/HA/7, Environment Canada (1990).

Znidarcic, D., R.L. Schiffman, and M.K. Malone, " The Flow Pump Test Permeability Test", Report prepared for the U.S. Bureau of Reclamation, Geotechnical Division, Department of Civil, Environmental and Architectural Engineering, University of Colorado (August, 1986).

Appendix

Sources for Test Methods

The testing methods specified in Table 2 can be obtained from the following sources:

1) WTC Protocol (Stegemann and Côté, 1991; Appendix B):

Method 1:	Specimen Preparation and Curing
Method 2:	Bulk Density
Method 3b:	Specific Gravity - Dry Method
Method 4:	Water Content
Method 5:	Falling-head Hydraulic Conductivity
Method 6:	Unconfined Compressive Strength
Method 9:	Equilibrium Extraction
Method 11:	Acid Neutralization Capacity

Ms. J. Stegemann
Wastewater Technology Centre
867 Lakeshore Road, P.O. Box 5068
Burlington, Ontario
L7R 4L7

2) United States Bureau of Reclamation (1988): Heat of Neutralization Method to determine cement content

Mr. P.C. Knodel
Geotechnical Services Branch
US Department of Interior
Bureau of Reclamation (Denver Office)
P.O. Box 25007, Building 67
Denver Federal Center
Denver, CO 80225-0007

3) ANSI/ANS-16.1: Measurement of the leachability of solidified low-level radioactive wastes by a short-term test procedure

American Nuclear Society
555 North Kensington Avenue
La Grange Park, IL 60525

4) ASTM Standards:
G 21-70 Standard Practice for Determining Resistance of Synthetic Polymeric Materials to Fungi

G 22-76 Standard Practice for Determining Resistance of Plastics to Bacteria

D 4842-89 Standard Test Method for Freezing and Thawing of Solid Waste

D 4843-89 Standard Test Method for Wetting and Drying of Solid Waste

American Society for Testing and Materials
1916 Race Street
Philadelphia, PA 19103

5) U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP) Federal Register, Part II, Vol. 55, No. 61, Thursday, March 29, 1990.